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MEASUREMENT OF AIRCREW PERFORMANCE: THE FLIGHT DECK WORK-LOAD AND ITS RELATION TO PILOT PERFORMANCE

Erwin A. Lauschner

Advisory Group for Aeronautical Research and Development
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Measurement of Aircrew Performance

The Flight Deck Workload and its Relation to Pilot Performance

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MEASUREMENT OF AIRCREW PERFORMANCE:

The Flight Deck Workload and its Relation to Pilot Performance

Papers presented at a symposium held by the Aerospace Medical Panel of AGARD at Brooks Air Force Base, USA, on 14-15 May 1969

FOREWORD

In my capacity as Chairman of the Aerospace Medical Panel of AGARD it is a pleasure to introduce this collection of papers, which were presented at the USAF School of Aerospace Medicine, Brooks Air Force Base, Texas on 14 and 15 May 1969.

The decision to hold a symposium on the topic of "The Flight Deck Workload and its Relation to Pilot Performance" was made by the ASMP on the recommendation of its recently constituted Behavioral Sciences Committee. The topic is a broad one, so it was not possible to do more than highlight certain aspects of the problem in the one and a half days which were available.

The symposium drew attention to the difficulties associated with the quantitative assessment of workload, and the prediction of performance decrement consequent to high or prolonged workloads. Whereas the effect of specific components of workload (e.g. thermal stress) on pilot efficiency is understood to an extent which allows the aeromedical specialist to offer an evaluated opinion to the operational commander, a comparable situation does not yet exist when a more general assessment has to be made of the aviator's workload and the operational consequences predicted.

In the absence of any global solution to the problem it was reassuring to find work in progress in two major areas. One was concerned with the study of short-term high workload during approach and landing, the other with an examination of the factors, such as sleep loss and duty schedules, which determine the long-term workload.

These topics are of operational importance in civil as well as military flying. Accordingly, I was gratified to find that aeromedical specialists who represented these two interests contributed to the symposium, which I am sure provided an opportunity for the mutual exchange of information between workers in this field from Europe and the North American Continent.

Erwin A. Lauschner

Professor Dr Erwin A.Lauschner
Brigadier General MC, GAF
Chairman, Aerospace Medical Panel
AGARD/NATO

AVANT-PROPOS

En ma qualité de Président de la Commission de la Médecine Aérospatiale j'ai le plaisir de présenter ce recueil de communications qui ont été faites au Collège de la Médecine Aérospatiale de l'USAF, Brooks Air Force Base, Texas, les 14 et 15 mai 1969.

La décision d'organiser un Symposium consacré au thème "La Charge de Travail du Poste de Pilotage et son Rapport avec les Performances du Pilote" a était prise par la Commission sur proposition de son Comité récemment créé sur les Sciences du Comportement. Le domaine couvert par ce thème étant très large, il fallait se contenter, au cours du jour et demi dont on disposait, à mettre en lumière un certain nombre d'aspects seulement de ce problème.

Le Symposium a attiré l'attention vers les difficultés liées à l'évaluation quantitative de la charge de travail et à la prédiction du décrément de performance dû à des charges de travail élevées ou prolongées. Alors que l'influence, sur le rendement du pilote, d'éléments particuliers de la charge de travail (par exemple, la tension thermique) est suffisamment connue pour permettre au spécialiste aéromedical d'exprimer au pilote commandant de bord une opinion évaluée, cela n'est pas le cas lorsqu'il s'agit de faire une évaluation plus générale de la charge de travail de l'aviateur et d'en prédire les répercussions dans des conditions d'exploitation de l'avion.

En l'absence d'une solution globale du problème, il a été rassurant de constater que des travaux sont en cours dans deux grands domaines. L'un de ces domaines se porte sur l'étude d'une charge de travail élevée à court terme lors de l'approche et de l'atterrissage, et l'autre sur l'examen des facteurs, tels que perte de sommeil et programmes de service, qui déterminent la charge de travail à long terme.

Ces thèmes sont d'une importance opérationnelle tant pour l'aviation civile que militaire. J'ai été en conséquence très heureux que des spécialistes aéromedicaux s'occupant de ces deux intérêts aient fait des contributions au Symposium, qui, j'en suis sûr, a fourni l'occasion d'un échange d'informations entre ceux qui travaillent dans ce domaine en Europe et dans le continent nord-américain.

Erwin A. Lauschner,

Professor Dr Erwin A. Lauschner
Brigadier General MC, GAF
Chairman, Aerospace Medical Panel
AGARD/NATO

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FLIGHT-DECK WORKLOAD STUDIES IN CIVIL TRANSPORT AIRCRAFT

by Dr. J. S. Howitt

Civil Aviation Dept., Board of Trade

At the end of 1964 a small group was formed in the United Kingdom to investigate flight-deck workloads in civil aircraft. It consisted of two full-time members from the then Ministry of Aviation, a doctor and an operations officer, both pilots, and two part-time members, physiologists from the R.A.F. Institute of Aviation Medicine, Farnborough.

Since the group had limited resources it had to decide which of the many possible areas it was best suited to study. For instance it was felt that the detailed ergonomics side e.g. crew work-space, control characteristics, instrument presentation, etc. could probably be more profitably studied during the development of particular aircraft and was not the area best suited to the group's capabilities. It was, therefore, decided that we should study the effect of the total flying environment on the man and it soon became clear that the work could be conveniently divided into three distinct areas as follows:-

(i) The immediate workload: i.e. the workload experienced over any particular short period of time, e.g., take-off, descent, landing or, in military aircraft, the bombing run or the attack phase.

(ii) The duty-day workload: i.e. the sum total of the short-term workloads experienced during a working day.

(iii) The long-term workload: i.e. the effect of the sequences of working days over a particular roster pattern which would include such things as sleep patterns and time zone changes.

The methods we used were of necessity very simple and unsophisticated by laboratory standards. The situation in a civil transport aircraft on normal commercial operations is very different from that in a military or research aircraft. In fact the initial part of the work was largely an exercise in public relations. In these circumstances one has to rely entirely on the goodwill of the airline, the Pilot's Association and the individual pilots themselves, to be able to take biological measurements on the crews or even to be in the cockpits as an observer. Above all nothing can be done that will in the slightest way prejudice the skill and concentration of the crew or the safety of the aircraft. If one is following a crew through a long-haul duty roster one may be away two weeks or more and fly in four or more different aircraft so it is impracticable to have permanent recording installations in the aircraft. Similarly, since by law one has to travel on the passenger manifest, at each stop one has to pass through customs and immigration areas carrying the equipment with normal baggage. Finally, for many reasons, we found it best to be independent of aircraft power supplies and to be battery operated. This placed a severe restriction on the amount and type of equipment we were able to carry.

In the event, we were given full co-operation from the airlines and BALPA and quite remarkable co-operation from the crews we used as subjects. Our methods and results are best described under the three headings previously mentioned.

IMMEDIATE WORKLOAD

It was felt, at a very early stage, that in investigating the immediate workload we were interested in the man's level of arousal and its relationship to the complexity of the job in hand. There is at present no simple and direct way of measuring arousal, but there are several secondary measures which can be said to be indicators of change in arousal level e.g. skin conductivity, muscle tone, respiratory rate and heart rate. Of these we chose heart rate as being the most reliable, simple to record and offering the least interference to the subjects. The captain's E.C.G. was taken from three conventional chest leads: amplified, filtered and the R wave made to trigger a 300c.p.s. tone that was recorded on tape. At the same time the observer, who sat on the jump-seat behind the captain, recorded on the same tape a running commentary of events as they happened in the cockpit. On return from each trip the heart beats were counted in real time, plotted in the number of beats in each minute of the trip and then matched with events as recorded from the commentary. An example of the type of record obtained is shown in Fig. 1. This shows four day's flying on a six-day trip to Bangkok and return. The most obvious changes are those associated with take-off, top of descent, and descent and landing. On sectors when the first officer is flying, the record is still that of the captain and it can be seen that the peaks at take-off and landing are absent. On the full record there were too many minor points of interest to include in a short paper such as this but it can be seen that as well as flying activities such things as meals, speaking on the P.A. and sleeping and so on are easily identifiable. An example of how reliable an indicant of mental activity is the heart rate can be shown by two landings at Teheran. There are three beacons over which the aircraft must be positioned at particular heights and the records show peaks corresponding to each of the beacons during both landings.

When using heart rates as an indicant of arousal level it is essential to know your subject and his heart-rate well. For instance after several flights with this particular pilot we judged that, when his heart rate exceeded 150 beats in a minute whilst flying, he was at or near the peak of his arousal level that would seem desirable for maximum efficiency. It will be noted in Fig. 1 that at Bombay his heart rate exceeds 150. This was a difficult approach since it was a dark night, there had been some problems of radar identification, and Bombay at that time had a $3\frac{1}{2}$ degree glide slope on its I.L.S. which was uncomfortably steep for a Boeing 707. The arbitrary level of, in this case, 150 was admittedly no more than an informed guess gathered from experience. These records are now quite old (this was 1965) and we have advanced considerably since then.

Squadron Leader Nicholson, who is a member of our group, in a later paper, will describe how he has taken this a step further and, with the same pilot, has confirmed that when, during a landing, his heart rate reaches approximately 150 beats per minute there are other signs which suggest definite changes in his physiological state.

As an interesting side-line to this, we noticed that the captain's heart rate did not rise in the usual steps from top of descent to landing when the first officer flew the aircraft. We therefore thought it reasonable to suppose that, on difficult approaches, if the first officer brought the aircraft into say five miles out and at 1,500 feet and the captain then took over, the captain would start the final approach at a lower level of arousal and land the aircraft at a lower peak of heart rate. We arranged to carry out two trips to Hongkong and return with the same crew in a Boeing 707 and thus have two sets of landings, one with the captain flying the whole of descent and landing and the other with a shared approach. Fig. 2 shows the captain's heart rates for both types of landing and it can be seen at Calcutta and Hongkong where the normal landing produced very high heart rates the shared landing was markedly lower.

One final word on heart rates. We did for some time consider measuring r-r variability throughout the trip. We have done this on some of our records; in Fig. 3 the r-r intervals are plotted for the last part of an approach and landing by a captain of a BAC 111. The variability is low while he is flying on instruments down to 'field in sight', (F.I.S.). When the field is in sight the pilot looks up and goes visual. In this particular instance he is in a good position, the weather is good, the landing is an easy one and the variability increases directly. We have done some ground experiments to see how useful this could be to compare the same task during different fatigue states and we find that, although certainly as mental work increases the r-r variability decreases, the difference between the same man on different days is so great that we have not found it useful to continue with this aspect of heart rate analysis.

To summarise: there is still very much more work to be done in this field but evidence obtained so far does suggest that a reasonable assessment of immediate workload may be obtained by physiological measures in the not too distant future.

DUTY DAY

For assessment of the 'duty day' workload we used three approaches:-

1. We collected all the pilot's urine, in separate samples throughout the trip, for return to the R.A.F. Institute of Aviation Medicine and subsequent biochemical analysis.

2. At approximately $1\frac{1}{2}$ hrs. after the final landing on each flying day, and at 18.00 hrs. on each rest day, we asked the pilot to fill in a 'state of fatigue' questionnaire which gave a score, with a maximum of 20 points, of the pilot's subjective feelings of fatigue.

3. A variety of post-flight psychological tests were used in an attempt to show changes in performance that could be correlated with fatigue or with length of duty day.

The urine samples were taken specifically before and after sleep, before take-off and after landing. All the other times were left to the subject's natural wishes. The main estimations made in the subsequent analyses were of adrenaline, nor-adrenaline, sodium, inorganic phosphate, potassium, nitrogen and parahydroxyphenyllactic acid. Of these, adrenaline was found to be by far the most consistent and useful. However, although the results were interesting, it was not found possible to use adrenaline as a finely quantitative measure of work done in the sense of work leading to fatigue. This is understandable when one remembers the many subtle influences that govern the excretion of adrenaline. Thus, two seemingly identical flights would show differences in adrenaline excretion by a factor of as much as 2 if one were at night and the other by day. Again, on occasions a pilot's adrenaline output could be more on his rest day than on his flying day. Also it was found that one somewhat alarming incident lasting perhaps 30 seconds could increase the duty day's total adrenaline output by as much as two thirds.

Our use of post flight pyschological tests led to disappointment. The restrictions on the weight and bulk of equipment we could carry, and the limitation on the pilot's time after a long flight that we felt we could reasonably ask for, limited the types of tests we could apply. We used simple mathmatical and card sorting tests and a modified Stroop test. We obtained no consistent results that could be correlated with work done or with the subjects fatigue estimates.

The post flight subjective fatigue scores were most useful and the subjects were very soon able to use them consistently. Each subject had his own interpretation of the questionnaire so that there could be no direct comparison of scores between subjects, but for each subject the comparative scores matched very well the observer's estimate of the man's day's work and his apparent level of fatigue.

Thus to summarise the duty day: we have tried very hard to find an objective measure that can be used to quantify accurately the pilot's daily workload or its effects. We have so far failed to find such a measure but a subjective estimate of fatigue by a well motivated subject is a useful alternative.

LONG TERM WORKLOAD

We know of no biological measure of long term workload. One of the most consistent correlations in our earlier studies of long-haul operations was between sleep patterns and post flight fatigue scores. In consequence, we have concentrated on sleep patterns and duty sequences in the long term. Our method is to issue the crews with specially printed diaries in which they record each day the time they go to sleep, the time they wake, duty times and the answers to a fatigue questionnaire. From these we have obtained much useful information on both long and short-haul operations.

An example is shown in Fig. 4. It shows the sleep patterns and flying periods of two subjects, Captain C10 and C11, on a two week shuttle between Las Palmas and Rio de Janeiro. The sleep has been plotted horizontally in real time units and the 'sleep credit' has been shown vertically on an arbitrary scale. The rate at which sleep credit is assumed to be exhausted is denoted by the diagonal lines whose slopes are at an angle to the vertical, equivalent to the loss of eight hours sleep credit in sixteen waking hours.

The flying duty periods are plotted on the same base-line as the sleep periods and where the 'credit' slope reaches the base line is where the subject is presumed to have exhausted his sleep credit. In this admittedly oversimplified representation no attempt has been made to adjust the sleep credit for previously incurred sleep debts.

Captains C10 and C11 carried out the same flying programme, one 2 weeks after the other. There was one slight difference in that, due to an engine failure, Captain C10's flight on the morning of Day 9 was curtailed by an emergency return to Las Palmas and the flight completed later in the day.

A comparison between the sleeping patterns of Captains C10 and C11 shows that Captain C10 was able to arrange his sleep in a much more satisfactory manner than was Captain C11. This was due more to Captain C11's inability to sleep during the day than to lack of planning. The points at which Captain C10's 'credit slopes' cut the base-line were, in most cases, at the end or after the end of his flight. On Day 3 he was some 3 hours short of his target and also on Day 13 although this latter was difficult to judge since the sleep he got between 17.00 and 23.00 was described by him as 'dozing and reading' and, therefore, has been plotted in dotted lines.

Captain C11, on the other hand, did not on any occasion achieve the target of completing the flight before running out of sleep credit. On one occasion, Day 9, he was out of credit before the flight began.

Fig. 5 shows the three-day moving average of sleep for the two captains. Also are shown their mean sleep per day for the duty period and their normal mean sleep per day calculated from a period of leave when their sleep was not affected by duty flights nor the recovery period from previous flights. It can be seen that, on the shuttle, both captains' means are well short of their normal but that Captain C11 is far worse than Captain C10. This is reflected in the subjective fatigue scores (marked on the sleep and duty base-line) of which Captain C11's are markedly higher at the end of the period than at the beginning whereas Captain C10's show little change. This was confirmed by the observer's impressions that, although both captains were tired at the end of the fifteen days, Captain C11 was very much more tired than C10.

Both subjects incurred long-term sleep debts which continued to accumulate during the second week despite a degree of adaptation to the reversal of day-night activity. It was, therefore, logical for the airline to reduce the duty period from two weeks to one; it did this and there were no further complaints of fatigue.

Space does not allow further illustrations. Similar methods were used over a four month period with a group of short haul jet pilots and the importance shown of sleep patterns and duty sequences.

CONCLUSION

To conclude, one can say that there are three main areas of interest in aircrew workloads. With the first, the immediate workload, there is now evidence to suggest that before long it will be possible to use physiological measurements to assess the pilot's level of arousal in terms of those which are optimal for the particular flying task.

In the second, the duty-day workload, we do not as yet have anything better to use than the pilot's subjective opinion. One hopes that eventually a more objective and quantitative measure might be found and we will continue with the biochemical approach.

In the third, long term workload, comparatively simple methods such as the keeping of diaries by the crews can give much valuable information regarding the desirability or otherwise of particular duty sequences and sleep patterns.

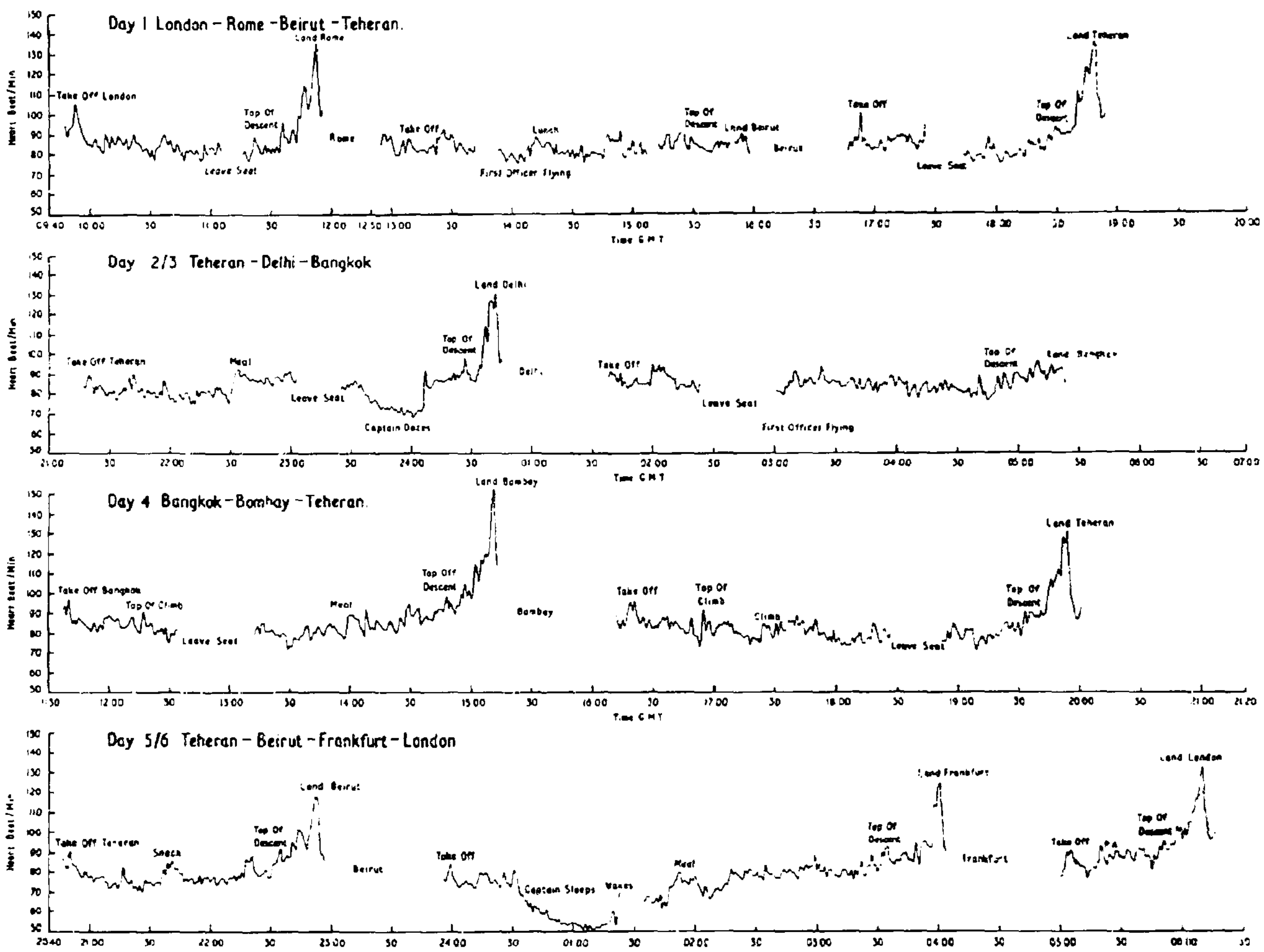


Fig. 1 Captain G10. 6 day London - Bangkok and return. Summer 1965

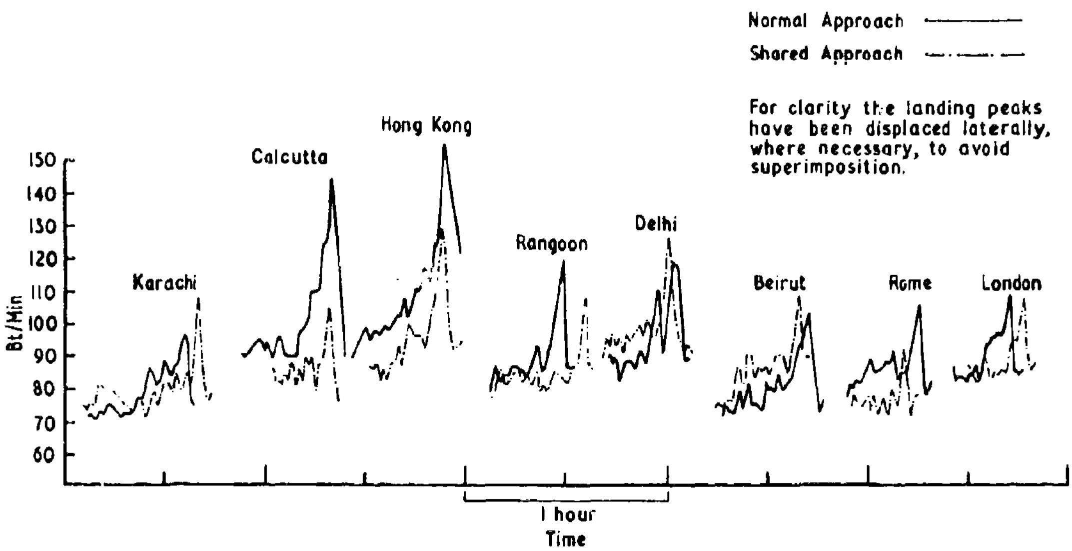


Figure 2

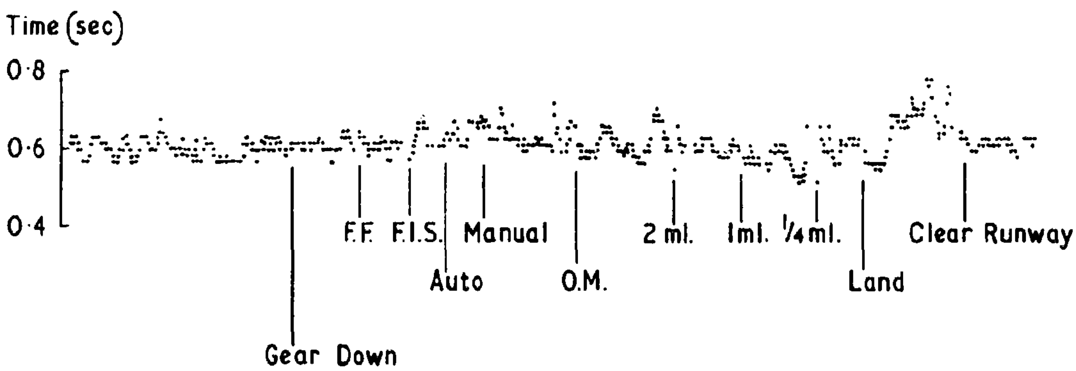
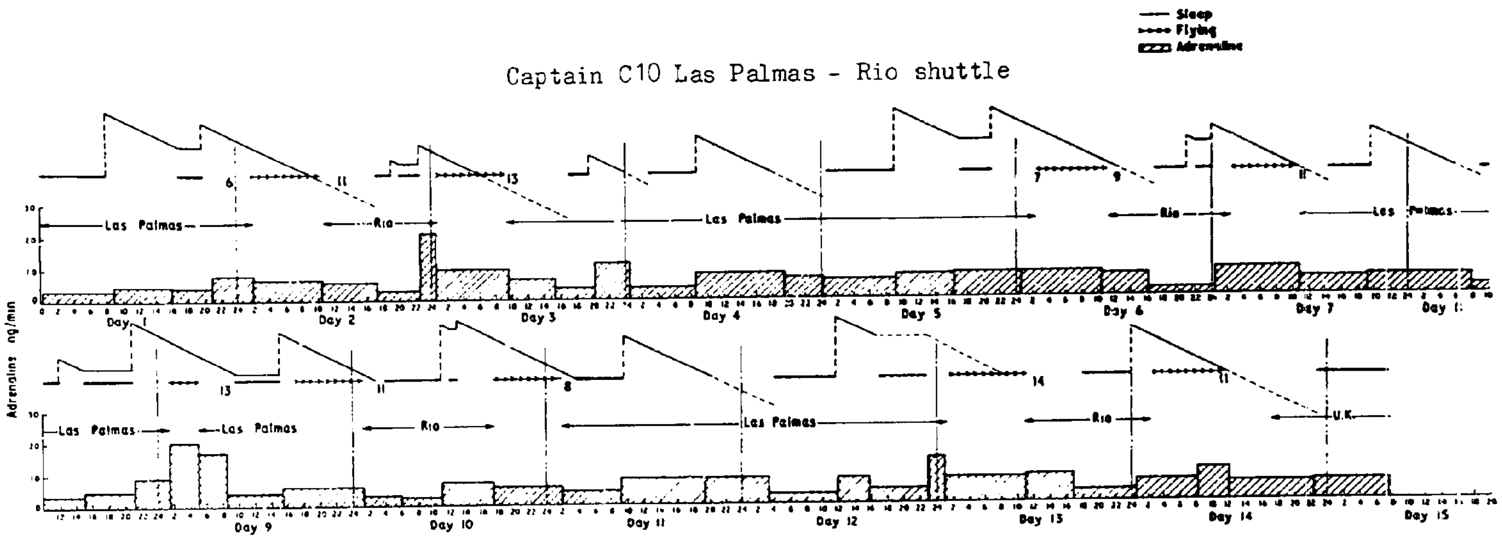


Fig. 3 r-r intervals on landing

Captain C10 Las Palmas - Rio shuttle



Captain C11 Las Palmas - Rio shuttle

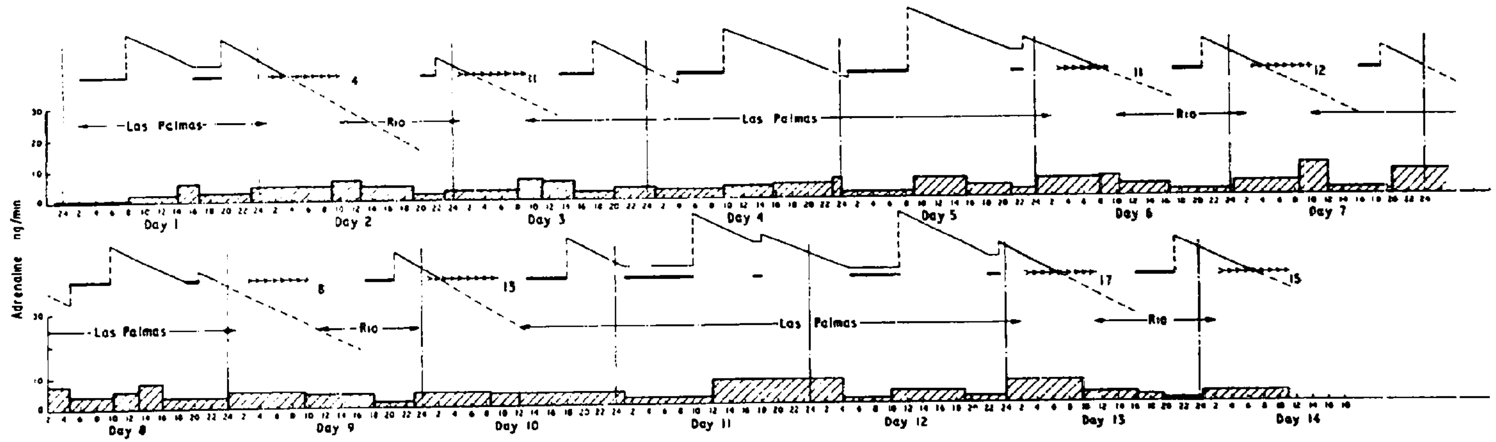


Figure 4

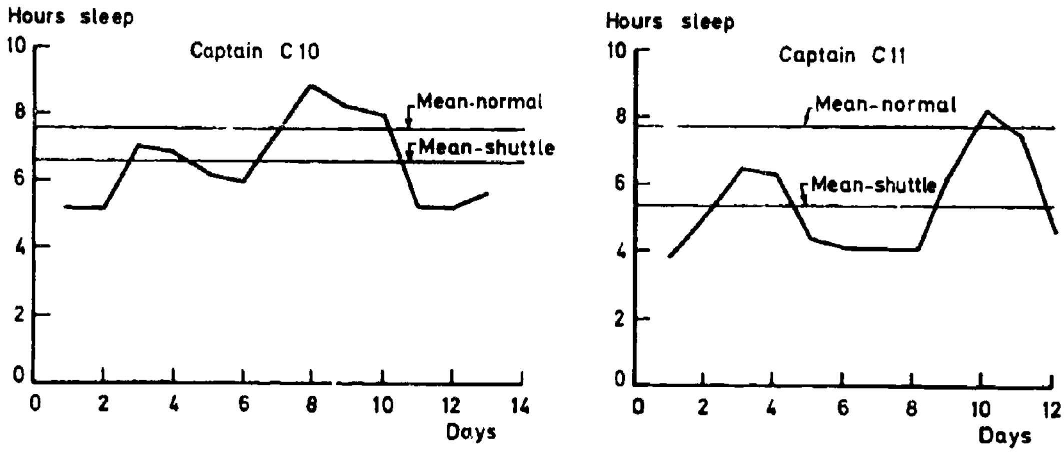


Fig. 5 Las Palmas - Rio shuttle. 3 day moving averages of sleep

SUMMARY

The term 'Work Load Study' can be interpreted in many ways depending on one's particular interest and point of view.

During the past four years a small team, from the Board of Trade Aviation Department and the Royal Air Force Institute of Aviation Medicine, has been conducting field studies in civil airlines during both long-haul and short-haul operations. The team have found such studies can be conveniently divided into three main areas; that associated with short term, or instantaneous work load, that associated with accumulated effects of work loads over a particular period and that associated with the total working environment.

Some of the methods used and the indications for further areas of research are discussed.

ENERGY COST OF PILOTING FIXED AND ROTARY WING ARMY AIRCRAFT

By

LTC Delvin E. Littell, MC
U. S. Army Aeromedical Research Laboratory
Fort Rucker, Alabama

SUMMARY

The energy cost of piloting three U. S. Army helicopters (light, utility and medium) and one utility fixed wing aircraft was investigated. Energy expenditure was calculated from expired minute volume and expired air oxygen content measured during the basal state and in normal flight conditions. Data were collected on a total of sixteen pilots, five of whom flew all three helicopters. All of the helicopter pilots were experienced test pilots. The data indicate that, for these pilots, and flying conditions studied (level flight in good weather) and aircraft, the energy cost must be classed as very light work, averaging 1.79 kcal/minute. The energy cost of flying the fixed wing aircraft by less experienced pilots was similar to previously reported energy expenditures for such aircraft. The data were segregated to separate measurements made at altitude from those made during flight in close proximity to the ground (take off, hover, etc). In three of the four aircraft, the pilot's energy expenditure was greater when ground contact was possible.

IN ORDER TO evaluate such factors as fatigue, decrement of performance, man-machine interactions, and thermal stress, a study was conducted to accumulate data concerning the energy cost involved in flying current Army aircraft, particularly helicopters.

It is surprising that there is so little data on the energy costs of flying when one considers the wealth of available information about the energy costs of performing a wide range of other human activities. Passmore and Durnin's comprehensive review in 1955 reported only two studies in only one of which were measurements made during flight. Twelve years later, these same reviewers had found no new studies. As far as we can find, there is no information available about the energy costs of flying helicopters. Earlier studies have all been done in fixed wing aircraft. It is generally accepted by dual rated pilots that rotary wing aircraft are more difficult to fly than fixed wing aircraft. A pilot is always "flying" them, by continual adjustments of the cyclic and pitch control sticks and the rudders. It has been said that flying helicopters is "like rubbing your head, patting your stomach, and tapping time to Dixie with both feet, all at once".

We were concerned in this initial study with energy costs involved in flying light (OH-6A), utility (UH-1D), and medium helicopters, and also a typical utility fixed wing aircraft (U-6A).

METHODS

SUBJECTS. The subjects studied were sixteen men, all experienced aviators. The twelve helicopter pilots fly test and evaluation missions for the U. S. Army Aviation Test Board, Fort Rucker, Alabama. The four U-6A pilots may be considered as typical Army aviators. The mean age of all pilots was 39.5 ± 1.4 years; mean nude weight was 78.7 ± 2.6 kg; mean height was 176.1 ± 1.26 cm; mean surface area was $1.96 \pm .04$ m^2. They wore an average clothing weight while flying of 4.51 ± 0.16 kg. Their experience as aviators may be represented by their mean flying time of 7025 hours, with a range of 1500 to 13,200 hours.

MEASUREMENT PROCEDURE. Energy expenditures were calculated from expiratory minute volume and expired air oxygen content measurements made under basal conditions and during normal flight duties of pilots. Each pilot wore a standard rubber oxygen face mask, (service MS22001) which covers the nose and mouth, fitting under the chin, and which had been modified to allow respiration through a T-shaped plastic one-way breathing valve (Collins J catalog no. P-307) attached to the mask. The mask and J valve combination had a dead air space of less than 175 cc. Each pilot was accustomed to wearing the mask and could perform piloting tasks without significant interference by the mask. Expiratory minute volumes were calculated from total expired volume as measured by the Franz Mueller gas meter. A 0.6% sample in Mueller bags was dried and oxygen percentage measured by a paramagnetic oxygen analyzer (Beckman Model E-2). All volumes were corrected to STPD, based on the barometric pressure measured by a standard surveyors field barometer carried within the aircraft. Kilocalories were calculated by the Weir formula, and surface area was computed from the nomogram of DuBois.

An electrocardiograph was recorded from two sternal electrodes on the magnetic tape of an electrocardiocorder, from which EKG paper strips were reproduced. The number of QRS complexes during a twelve second time interval were counted for heart rate calculation.

Basal measurements were made early in the morning, ten-twelve hours postprandial, while the subjects were lying quietly in a semi-darkened room. During the flying period, the first measurements were taken during a five-minute rest period prior to starting the aircraft engine (sitting). The second measurement period, during hover or taxi of the aircraft, averaged four minutes in duration. The third measurement period began at take-off and lasted for approximately two minutes until the aircraft was leveled off at 1500-2000 feet. A five-minute period of level flight (level 1), was followed by a seven-minute period during which the pilot flew in a typical holding pattern (aerobatics), with measurements made during the last five minutes. Level flight was performed for another five minutes (level 2), and descent measurements began approximately two minutes before touchdown and were continued until the aircraft landed. All values are reported as the mean plus or minus one standard error of the mean.

RESULTS

Basal values for metabolism and heart rate were secured from fifteen of the men. Their mean $\dot{V}_E$ was $6.52 \pm .20$ L/minute; mean $\dot{V}_{O_2}$ was 237 ± 0.7 cc/min; mean metabolism was 35.1 ± 1.6 kcal/m^2-hr. (1.14 ± 0.04 kcal/min); and their mean basal heart rate was 61.5 ± 1.6 bpm. There is no basal metabolism data for one helicopter pilot, who flew all three helicopters, due to technical problems. A repeat of this data point was not possible owing to non-availability of the subject.

Because some of the pilots were scheduled to fly more than one type of helicopter during the time of the study, data were collected from five pilots who flew all three helicopters (Table 1). The mean total flying hours for these five pilots was 8,640 (4,000-13,000) hours, the mean age was 40.0 ± 3.3 years; the mean body surface was 1.93 ± 0.04 m^2. Their basal heart rate was 61.2 ± 2.5 bpm and their basal energy expenditure ($N = 4$) was 38.6 ± 4.4 kcal/m^2-hr. ($1.08 \pm .017$ kcal/min).

Figure 1 presents a comparison of the energy cost of handling these aircraft near the ground and at altitudes above 500 feet, for the pilots in Table 1. The data for the measurement periods of hover, taxi, take-off and landing are used for low altitude (ground) operation. Measurements during level flight 1 and 2, and aerobatics are used for operation above 500 feet (air). The basal and sitting measurements are presented for comparison.

DISCUSSION

We expected to find a significant difference in the energy cost of flying the three different aircraft because of the varying degree of mechanical complexity involved. We found no such significant difference.

We did expect to find significant differences in the energy cost of piloting the aircraft near to the ground and at a significant altitude. These expectations were realized. Hovering of helicopters and taxiing the fixed wing aircraft require that the pilot provide frequent and careful control motions to stabilize a dynamically unstable aircraft. The greatest danger of catastrophic ground contact exists during take-off and landing. The pilot must maintain more precise control of aircraft under these conditions than during operation at a significant altitude.

The measured energy expenditures suggest that fixed wing aircraft impose a greater work load. This may result from differences in pilot experience or weather (fixed wing aircraft are more influenced by surface winds) or inherent differences between fixed and rotary wing aircraft.

Review of the literature reveals that for fixed wing aircraft in combat or routine flying, average energy expenditure are 2.9 kcal/min and 1.7 cal/min. These results, when compared to our findings for rotary wing aircraft (average 1.72 kcal/min) suggest, at least for experienced pilots, that there is no gross difference in the overall energy cost of piloting aircraft.

Heart rates in general parallel the energy expenditure and at no time were high enough to suggest a cardiovascular response to emotional or physiological stress. Neither the heart rates nor energy expenditures measured in this study suggest that under the conditions of this study, the mechanical work of piloting these aircraft is a significant cause of pilot "fatigue".

This study was designed to measure the energy cost of the piloting task during actual flight and to provide information not presently available, particularly for helicopters. We believe that the energy cost of flying helicopters presented here represents the minimum values. We suggest that the energy cost of flying these aircraft by less experienced, or less confident pilots will be significantly greater. We are continuing this study in order to increase the variables of aircraft type, pilots, and flight conditions studied.

We wish to express our gratitude to the President of the U. S. Army Aviation Test Board and the pilots of the Logistical Evaluation Division who willingly cooperated with us on this study. A special word of thanks to LTC Robert J. T. Joy, MC who assisted in this study and SP5 Lawrence Kelly in preparation of this paper.

Aircraft	OH-6A			UH-1D			CH-47A		
Flight Mode \ Variable	H.R. bpm	kcal m^2/hr.	kcal min.	H.R. bpm	kcal m^2/hr.	kcal min.	H.R.* bpm	kcal m^2/hr.	kcal min.
Sitting	80.4	49.0	1.57	73.2	47.6	1.53	91.0	65.3	1.47
	6.7	4.9	.17	5.9	6.5	.22	6.4	8.2	.29
Hover	88.4	69.9	2.24	73.4	55.4	1.77	93.5	60.9	1.96
	11.3	6.1	.16	5.5	8.2	.24	9.1	2.7	.12
Ascent	86.8	64.0	2.06	74.2	53.2	1.70	92.5	65.1	2.08
	10.4	6.8	.21	6.1	6.6	.20	7.6	6.0	.16
Level 1	80.6	45.5	1.47	73.2	49.2	1.59	92.8	52.1	1.68
	10.8	2.1	.10	7.3	2.6	.09	6.2	2.3	.09
Aerobatics	88.4	47.9	1.54	76.0	48.5	1.56	92.2	53.6	1.72
	16.3	3.4	.08	8.4	3.3	.11	11.7	2.5	.11
Level 2	82.6	44.9	1.45	76.6	44.8	1.44	91.3	50.8	1.67
	9.5	3.1	.13	10.0	3.6	.12	8.2	3.2	.12
Descent	80.6	51.2	1.65	82.6	46.2	1.48	89.0	54.6	1.76
	6.1	5.7	.19	12.2	6.0	.19	10.4	3.3	.13
Flying hours by aircraft	146(30-300)			1,860(700-4,500)			430(200-1,000)		

*H.R. values are for N = 4.

Table 1 Values for heart rate and energy expenditure for the same five pilots flying three different helicopters. The flying hour data are expressed as means and range. All other values are means (upper left) and standard error (lower right).

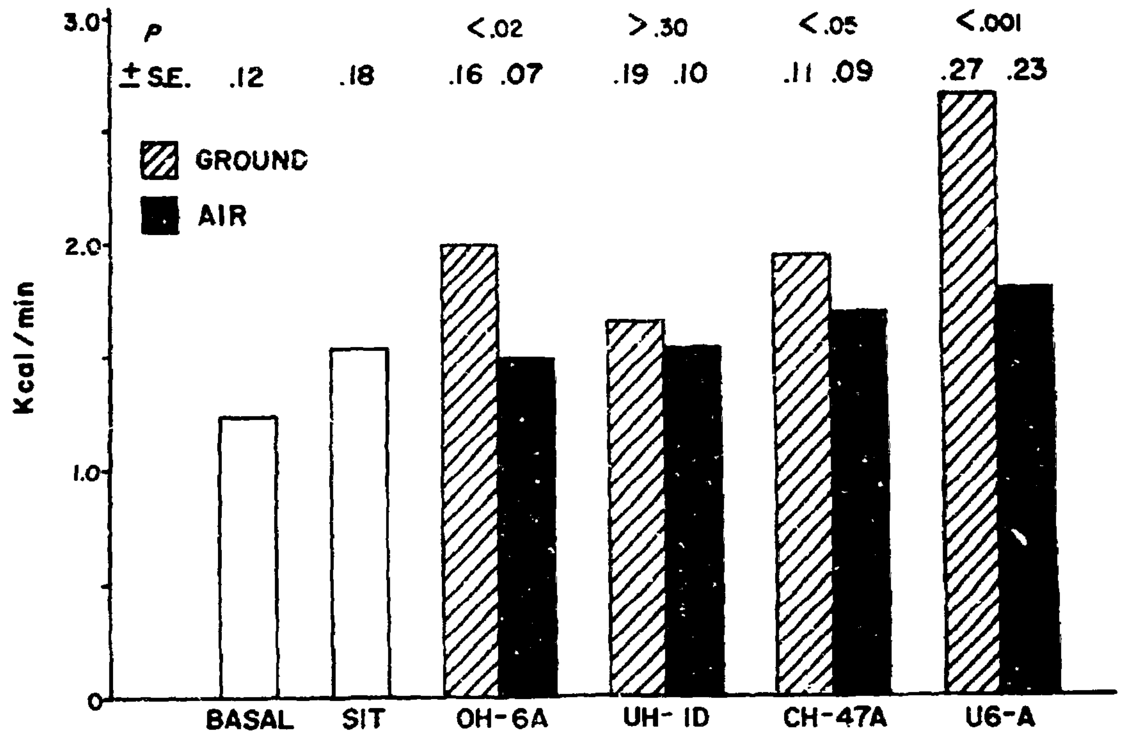


Figure 1 Energy expenditure for operation near the ground compared with operation at altitudes above 500 feet where ground contact is not an eminent threat.

PSYCHOMOTOR PERFORMANCE UNDER THERMAL STRESS: A CRITICAL APPRAISAL

by

R. Douglas Jones

Research Psychologist
Aviation Branch
Systems Research Laboratory
U.S. Army Human Engineering Laboratories
Aberdeen Proving Ground, Maryland

SUMMARY

MUCH OF THE previous work in thermal stress utilized subjects performing heavy physical labor under conditions of extremely high temperature and humidity. Based on the assumption that performance remains "normal" as long as body thermal equilibrium is maintained, these early investigations provided valuable data with respect to physiological adaptation and maximum tolerance times.

Unfortunately, over the past decade, the assumption of "physiological adequacy" and the data supporting it have become less and less relevant to the problems of quantifying the effects of less severe thermal environments on complex human performance. In addition, the thermal stress literature reflects a wide divergence of opinion regarding the selection, interpretation, and administration of such variables as stress indices, exposure times, acclimatization periods, etc. Moreover, as a consequence of the failure to standardize experimental variables, there is currently little agreement among researchers on either the significance, magnitude or direction of performance change as a function of the thermal environment.

The increasing demand for design standards applicable to crew station thermal environments would seem to necessitate some modification of approach in future thermal stress research. In general, changes in the basic research strategy should include:

1. Adoption of a standardized index representing all relevant environmental parameters acting to produce what is now loosely termed "heat."

2. Investigation of those thermal conditions expected to obtain in the predicted operational environment for a given man-machine system (rather than those capable of being produced only in a climatic chamber).

3. Greater emphasis on psychological variables such as learning, motivation and personality as they interact with both environmental and task variables.

4. A new definition of "stress" in terms of changes in a subject's ability to perform a given task rather than his physiological adaptation.

5. Increased attention to the kinds of increasingly complex performance demanded of the human operator in modern man-machine systems.

IN 1945 THE British psychologist N. H. Mackworth initiated the first comprehensive, systematic investigation of the effects of thermal stress on psychomotor performance. In demonstrating that certain types of skilled performance are subject to degradation under selected conditions of high ambient temperature, Mackworth provided the first empirical refutation of what Connell (1948) later termed "The Concept of Physiological Adequacy." This concept is based on the assumption that behavior will remain normal as long as the body's thermal equilibrium can be maintained. Unfortunately, although the evidence adduced for this assumption derives almost exclusively from studies of heavy physical labor in extreme thermal environments, it has had a dominant and continuing influence on the methodological approach to thermal stress research.

Whether explicit or implicit, past reliance on the validity of this assumption has tended to emphasize the response characteristics of physiological systems, often to the exclusion of other potentially valuable dependent variables. For example, today we know a great deal about the adaptive mechanisms of the cardio-vascular system under heat stress; we know very little about either the duration, magnitude or direction of changes in an individual's ability to perform, under heat, the increasingly complex psychomotor tasks associated with piloting an aircraft. Indeed, even when "psychomotor task" is broadly interpreted to mean a coordination of sensory, cognitive and motor processes, we find that fewer than 50 thermal stress studies employing this type of performance have been generated during the 24 years following Mackworth's work. Taken as a whole, these studies, in addition to reflecting a sporadic approach to thermal stress research, often present directly opposed conclusions regarding the type of performance change to be expected under conditions of high ambient temperature. The remainder of this paper is devoted to an examination of some experimental variables whose use and misuse have contributed to the conflicting reports in the literature. In addition, criticism is coupled, wherever possible, with suggestions for improvement of future work. The analysis begins with a brief review of the literature itself.

THERMAL STRESS LITERATURE - IN BRIEF

THERE ARE A number of bibliographies and reviews available on this subject (Bell & Provins, 1962; Groth & Lyman, 1963; Hendler, 1963; Stevenson & Johnson, 1967; Stevenson & Trygg, 1966; U.S. Army Tropical Test Center, 1967; Wing & Touchstone, 1963). Unfortunately, despite their publication dates, none of these compilations are recent or inclusive enough to allow an accurate appraisal of the effects of thermal stress on complex "mental" or psychomotor performance. The only recent review in this area was done by Wing (1965). He examined 15 experiments in order to determine the upper limits of "unimpaired mental performance." Since his goal was to plot performance decrement as a function of exposure times, however, the experiments chosen were necessarily limited to those in which some decrement was, in fact, reported. The major objection to such a procedure is that it tends to ignore or minimize the existence of studies which report no change or, in some instances, improvements in performance. It is important that such divergent results be clearly acknowledged. Only then can comparisons be made with respect to experimental designs, apparatus, subjects, etc. Such comparisons are necessary not only in reconciling conflicting data, but in establishing a reliable basis for the selection and/or control of relevant variables in future work.

In comparing stress vs. nonstress performance in a given task, only three outcomes are possible: (1) improvement, (2) decrement, or (3) no change. Within each of these categories, studies included in the present review are further classified according to the type of performance investigated. These performance areas are similar to those used by Wing & Touchstone (1963), and include the following: (1) sensory thresholds and reaction time, (2) vigilance and perception, (3) psychomotor performance, and (4) "mental" performance. These categories are neither mutually exclusive nor exhaustive; they are primarily for convenience and represent only one of a number of possible classification systems. For quick reference, the pertinent research is listed in Table I.

SELECTION OF VARIABLES FOR FUTURE RESEARCH

IN GENERAL, the literature reviewed provides no clear-cut criteria upon which to base predictions of mental or psychomotor performance under thermal stress conditions. The basic lack of agreement between the various studies is primarily the result of a generalized failure to standardize experimental conditions. The use of a wide variety of temperature levels, exposure times, etc., makes any direct comparison of results difficult. The studies can, however, be profitably examined under the following assumption: if the application of differing levels (or the omission) of an experimental variable leads to conflicting conclusions regarding performance, then the effects of that variable must be controlled and accounted for in future research. I have summarized what I consider to be a majority of such variables in Table II. It is obvious from the scope of this table that time and space limitations prohibit any detailed description of the relative contributions of subject, task, and environmental variables. Therefore, I would like to focus at this time on the role of environmental and physiological variables in thermal stress research.

TABLE I

LITERATURE SUMMARY

PERFORMANCE MEASURED	EXPERIMENTAL TEMPERATURES			EXPOSURE TIMES		N	DIR OF PERF CHANGE			AUTHOR
SENSORY THRESHOLDS & REACTION TIMES	Dry Bulb °F	Wet Bulb °F	% Rel Hum	Hrs	Min		+	0	-	
Simple Reaction Time	126		25-40		210	24	X			Lovingood, et al., 1967
" "	100	80	(ET=86)	6		18	X			Reilly & Parker, 1967
Simple & Serial RT	86	86	100	6		8		X		Ivy, et al., 1944
" "	117	85	17	6		8		X		" "
" "	90	83		21		20		X		Pace, et al., 1945
" "	108	83		3		20		X		" "
Serial RT	92-104				2.5	14		X		Peacock, 1956
Tactile Sensitivity	104		30	Task Det		72			X	Russell, 1957
Serial RT	90-104		90-95	1,2		7			X	Fraser & Jackson, 1955
VIGILANCE & PERCEPTION										
Spatial Orientation							X			
Visual Vigilance	100	80	(ET=86)	6		18	X			Reilly & Parker, 1967
Perceptual Speed							X			
Auditory & Visual Vig.	113		(ET=86)		20	12	X			Poulton, et al., 1965
Auditory Vigilance	Body Temp = 101°F				63	12	X			Wilkenson, et al., 1964
Visual Vigilance	100-115		4-24	4		12		X		Loeb, et al., 1956
" "	104, 122		20	1, 2&3		9		X		Carlson, 1961
Auditory & Visual Vig.	85-145	76-117		1/3-4		8		X		Bell, et al, 1964
Auditory Discrim.	95	70, 92		6 1/2		10		X		Fine, et al., 1960
Visual Vigilance	85	75	(ET 79)						X	Mackworth, 1946a, b
Auditory Vigilance			(ET79-97)						X	" 1961
Visual & Auditory Vig.			(ET81-86)						X	Pepler, 1958
Peripheral Vision	105	95	(BET 95)		140	18			X	Bursill, 1958
PSYCHOMOTOR										
Rapid Line Drawing	115			2		36	X			Vaughan, et al., 1968
Mirror Tracing	100	80	(ET=86)	6		18	X			Reilly & Parker, 1967
Wrist-Finger Speed							X			
Hand-Finger Dexterity	126		25-40		210	24	X			Lovingood, et al., 1967
Muscular Control, Eye-								X		
Hand Coord, Pursuit &	100	80	(ET=86)	6		18		X		Reilly & Parker, 1967
Compensatory Tracking								X		
Pursu.. Tracking	104		30	Task Det		126		X		Russell, 1957
Arm-Hand Coord	126		25-40		210	24		X		Lovingood, et al., 1967
Pursuit Tracking	------- ET 86 ---------								X	Mackworth, 1945, 1961
" "	------- ET 81-86 --------								X	Pepler, 1953, 1958, 1960
" "	116	105			30	6			X	" 1959
Simulator "Piloting"	160, 210, 235		20-30	Physiol Det		4			X	Blockley & Lyman, 1951
Time Sharing, Target Prediction	100	80	(ET=86)	6		18			X	Reilly & Parker, 1967
Rotary Pursuit Tracking									X	Teichner, et al, 1954
COMPLEX "MENTAL"										
Addition (no attempted)	126		25-40		210	24	X			Lovingood, et al., 1967
Anticipatory Perception, Judgment	80, 90, 100	70, 80, 90			60	16		X		Bartlett, et al., 1955
Elec. Trng, Course	86-92					80		X		Mayo, 1955
Discrimination	85-100	75-90	(ET76-91)					X		Chiles, 1957
" "	85-110	75-90		1		10		X		" 1958
Anagram Solution	95	70, 92		6 1/2		10		X		Fine, et al, 1960
5 Digit Mult., IQ Test	109		40	2		4		X		Givoni & Rim, 1962
Discrimination	------- ET 76-91 ---------								X	Pepler, 1958
Auditory Recall	------- ET 90, 95 ---------			1		15			X	Wing, et al., 1965
No.Checking & Addition	160, 200, 235			Physiol Det		8			X	Blockley & Lyman, 1950
Simple Addition	Body Temp = 102°F				63	12			X	Wilkenson, et al., 1964
Time Perception					45	12			X	Fox, et al., 1967

TABLE II

VARIABLES RELEVANT TO STRESS RESEARCH

ENVIRONMENTAL

Indices of Stress

ET	Effective Temp.	1923
ETC	Effective Temp. Corrected	1932
EP	Physiol. Effect	1945
CET	Corrected Effective Temp.	1946
C.I.	Craig Index of Strain	1950
ETR	Effective Temp. & Radiation	1950
P4SR	Four-Hour Sweat Rate	1952
HSI	Heat Stress Index	1955
WBGT	Wet Bulb Globe Temp.	1956

Source of Stressor
- Climatic Chamber *vs*. Outside Ambient Conditions

Exposure Times
- Single *vs*. Repeated
- Continuous *vs*. Intermittent

SUBJECT

Physiological

Adaptive System Responses
- Hypothalamic-regulatory
- Metabolic-endocrinological
- Cardiovascular
- Respiratory
- Heat Storage

Acclimatization

Circadian Rhythms

Physical

- Age
- Sex
- Physique
- Physical Condition
- Nutritional State
- Health - Present & Past History

Psychological

Personality
- Skills & Abilities
- Motivation

Intelligence

Response "Set"

Fatigue

TASK

Type
- Complex *vs*. Simple
- Novel *vs*. Repetitive
- Continuous *vs*. Discrete

Validity
- Lab *vs*. Operational Situation
- (Face *vs*. Construct Validity)

Instructions
- Written
- Demonstration
- Verbal

Learning Factors
- Feedback -- Continuous *vs*. Discrete
- Reinforcement --
  - Learning *vs*. Performance
  - Extrinsic *vs*. Intrinsic
- Methods of Administration
  - Time, situation, physical environment
- Fatigue

Data Collection
- Measurement Scales
- Frequency of Measurements
  - Performance Averaging

Statistics
- Sampling --
  - Size - N = ?
  - Composition: random, stratified incidental
- Reliability -- normative data

Interactions
- Single *vs*. multivariate predictions
- Potentiation

ENVIRONMENTAL VARIABLES

INDICES OF STRESS. Much of the controversy regarding the effects of thermal stress stems from a failure to consider "heat" as a complex stimulus. Heat stress, as experienced by the human organism, is actually a result of the body's integration of the effects of (1) air temperature, (2) humidity, (3) air movement, and (4) radiant heat. As Minard (1964) pointed out:

> "A comprehensive index of environmental heat stress must evaluate the four physical factors of the thermal environment in the proportion to which each will effect the exchanges of heat by radiation, convection and evaporation between the human body and its environment under varying conditions of skin temperature and skin wetness (p.3)."

The developmental history of attempts to construct such an index began with the use of wet bulb temperature as the single explanatory factor (Bedford, 1961). The availability of increasingly accurate instruments and measurement techniques, in conjunction with subjective reports of thermal comfort, led to the subsequent inclusion of the remaining three factors (dry bulb temperature, air velocity, radiant heat). Usually, the addition of each new factor resulted in a newly titled index, and the proliferation of these indices is in part responsible for some of the difficulty in comparing studies of performance under heat stress. The terms "heat" or "high ambient temperatures" are frequently used by experimenters to refer to only one or two of the four components involved in the production of "stress." Many authors, for example, report experimental temperatures in terms of wet and dry bulb readings only, and give no information about air movement. Some studies list effective temperatures but provide no wet or dry bulb figures; others report dry bulb temperatures only, without reference to humidity. With the exception of Joy (1967), none of the studies previously reviewed attempted to assess the possible significance of radiant heating effects. Because a number of different thermal stress indices are still being employed, a chronology of their development is provided in Table II. It should be noted that these indices are primarily concerned with the physiological impact of heat on man's ability to work, and, in cases where a particular index value serves as a limiting factor for performance, it is generally physical performance which is being referred to.

In examining the various indices it becomes apparent that all are based, to some extent, on the previously described concept of physiological adequacy. As such, they are concerned with the metabolic heat loads generated in various thermal environments; these loads are usually assessed indirectly by the measurement of physiological parameters including heart rate, rectal and skin temperature, sweat rate, etc. Table III (Yaglou & Minard, 1957) provides an example of the relationship between the many indices and one such physiological measure. Unfortunately, correlation coefficients of this magnitude are seldom, if ever, obtained between performance and physiological responses.

TABLE III

CORRELATION BETWEEN HEAT STRESS INDICES AND EVAPORATIVE SWEAT RATE

Index	Correlation Coefficient with Evaporative Sweat Loss
ETR	.7899
CET	.7839
WBGT	.7798
Globe Temperature	.7232
ET (normal scale)	.6943
Dry Bulb Temperature	.5595
Wet Bulb Temperature	.4606

With reference to the selection of a particular index for research in heat stress, the ASHRAE Guide and Data Book provides the following summary and recommendations:

> "There is presently no one proven method for combining all of the component heat loads into a single value that would accurately indicate the degree of heat stress as perceived by an individual working or resting in a hot environment. The difficulty lies in the inability to simulate human response. Physical instruments can accurately integrate, but the human body has the ability to differentiate between component thermal effects and to make prompt adaptive changes which the instruments cannot do. Nonetheless, each of the indices will supply valuable information on which to base an informed opinion. The index or indices selected for use should depend upon the nature and extent of the problem, the equipment and facilities at hand, and the availability of personnel trained in the field of thermal stress (p. 107)."

Since this advice is somewhat general, let me give an example of how one might go about selecting a specific stress index. In the process, problems of selection criteria will become apparent. I have chosen as an example the WBGT index. In a prospective study, the selection of this index could be substantiated as follows:

1. In the presence of a radiant heat load, the globe temperature (GT) represents the balance between heat gained by radiation and heat lost by convection; in effect, it integrates radiant heat, air movement, and air temperature into a single reading. This GT reading used in conjunction with a WB thermometer takes into account the four physical components of the thermal environment without requiring a separate measurement of air movement.

2. Field tests of the WBGT index have proven it to be highly reliable in predicting decrements in physical performance. In 1954, Yaglou & Minard conducted tests on Marine trainees and found the index correlated well with a number of physiological measures taken during the training exercises. Subsequent summer studies at test stations in Arizone (dry heat) and Florida (humid heat) confirmed these findings. Additional trials in 1955 at the Marine Corps recruit training depot (Parris Island, South Carolina) resulted in the adoption of the WBGT index in 1956 by the Training Command at that installation; it replaced an index then in use which was derived from air temperature and humidity alone. Under the new program, vigorous training of new recruits (first three weeks of training) was suspended at WBGT readings of 85° or higher; at WBGT 88° or above, vigorous training exercises were suspended for all recruits. Despite hotter weather in 1956, the incidence of heat casualties dropped to 1/3 of the 1955 figure. In 1957 the NAS-NRC subcommittee on thermal factors in the environment included the use of WBGT levels in controlling physical activity and preventing heat casualties at British Air Force and Naval training centers. In 1960 the Marine Corps ordered the use of the WBGT index at all bases where unacclimatized trainees undergo physical training during hot weather. Finally, at a conference held in October 1966, members representing US Army Natick Laboratories, USArmy Engineer Research & Development Laboratory (now US Army Mobility Equipment R&D Center), and US Army Human Engineering Laboratories agreed to adopt the WBGT index to specify permissible levels of heat in Army helicopter crew stations.

3. Instrumentation for obtaining WBGT is relatively inexpensive and quite reliable. The British Army is currently developing and testing a prototype WBGT meter which will allow direct readout of the single index value (Peters, 1967).

4. WBGT correlates highly with two other indices currently in use, the CET (.9983) and the ETR (.9768), and will thus provide some basis for comparing results from the present study with those reported by other investigators.

Having selected an index, there remains the problem of specifying the values of that index to be used in the experimental situation. In applied research, index values can generally be chosen on the basis of those which: (1) are reported in the literature as correlated with and relevant to the type of performance under study, (2) are capable of being duplicated and controlled accurately in the laboratory, (3) permit subjects to perform for the required times (do not exceed physiological tolerance times), and (4) sample a range broad enough to allow some generalization to operational situations likely to be encountered in the "real world." In addition to these four, a fifth criterion is necessary when selecting WBGT levels, due to the structure of the index itself. The computational formula, WBGT = .7WB + .2GT + .1DB, indicates that (1) as long as the weighted sum remains constant, any or all of the component WB, DB and GT values can change without changing the WBGT index number itself, and (2) any change in the sum, however slight, will result in a new WBGT number. Thus, criterion 5 states that when selecting WBGT levels for heat stress research, the investigator must not only know the relationship of the index value to the performance being studied, he must also justify his selection of the particular combination of WB, DB and GT used to generate that value.

Prospective WBGT values, for example, of 85°, 88°, 90° and 101° could be chosen on the basis of the five selection criteria as follows:

1. Laboratory and field studies have reported decrements in both physical and psychological performance associated with temperatures in this range.

2. WBGT values of 85° and 88° have already been widely adopted as upper thermal limits for moderate and heavy physical activity as well as for specifying permissible crew static heat loads in Army helicopters. The studies which provide evidence for adopting such values are not directly applicable to pilot performance, but they do suggest that 85° and 88° are productive starting points.

3. These WBGT values can be accurately administered and controlled within most environmental test chambers available.

4. Previous research indicates that no problems will be met at 85° and 88° with subjects (Ss) engaged in a 2-hour performance regimen involving little or no physical labor. It is not known at present whether the 90° and 101° conditions can be tolerated physiologically for this period of time. These extreme values are included: (a) to bracket the upper limits for unimpaired mental and psychomotor performance, and (b) because these temperatures have actually been recorded in helicopter cockpits under summer flight conditions (Moreland and Barnes, 1969).

5. Some data is available for choosing values of WB, DB and globe temperatures for each of the WBGT levels. Table IV lists these values and the source from which they were obtained.

TABLE IV

COMPONENT VALUES FOR SELECTED WBGT LEVELS

WBGT No.	Component Values (°F) WB	GT	DB	Source
85°	87.00	73.00	95.00	Each set of figures represents a point on a psychrometric chart (USAERDL, 1956).
	69.00	123.50	120.00	The straight line connecting these points is the "Outside Design Curve" adopted by the Army committee on aircraft crew station thermal environments (USAHEL Memo, 14 Dec 66). The curve is based on a review of high temperature extremes in AR 705-15 and MIL-STD-210A, with modifications suggested by the Joint Army-Navy-Air Force Manual (TM-5-785) and USAF Climatic Center curves. In essence, the curve represents the probabilities associated with the joint occurrence of WB and DB temperatures during the hottest months, for the hottest areas, worldwide (McDonald, 1964). As such, it includes the highest values recorded in Viet Nam (Natick Labs, 1953: Martorana, 1966).
88°	78.60	114.40	100.90	Based on actual flight measurements of U.S. Army aircraft cockpit temperatures (Joy, 1967: Moreland & Barnes, 1969).
90°	88.99	100.14	97.00	
101°	95.10	122.20	106.70	

It can be seen from my example that a rigorous and comprehensive selection of WBGT levels is somewhat difficult at the present time. The difficulties are due, in part, to the fact that worldwide climatic data is available for only two of the three WBGT components; viz., dry bulb and wet bulb temperatures. This data is presented as probability curves for the joint occurrence of the highest wet and dry bulb readings, in the hottest areas of the world, during the hottest months of the year. What is needed to establish true index values for the WBGT scale is an expanded set of 3-variable curves representing the highest values of solar radiation which occur in conjunction with existing wet and dry bulb values. Fortunately, worldwide solar radiation data is currently being collected and, when available, should measurably increase the validity of the WBGT index. Given comprehensive solar radiation measures, it should be possible to accurately estimate (at a 90-95% confidence level) the highest ambient WBGT values for prospective pilot/aircraft operating environments. Once the reliability of such estimates is established, it will, of course, be necessary to determine the correlation between outside ambient and inside crew station thermal environments. These correlations will, in turn, permit the specification of more realistic design parameters for crew station thermal environments.

EXPOSURE TIMES. In addition to using a variety of experimental temperatures, investigators have also employed exposure times ranging from 17 minutes (Blockley & Lyman, 1951) to 6 1/2 hours (Reilly & Parker, 1967). The selection of exposure times has been dictated by practical rather than theoretical or empirical considerations. Thus, at extremely high temperatures and/or humidities, physiological tolerance and requirements for subject safety are the principal determinants for length of exposure. In more moderate thermal environments, those known to be physiologically tolerable for specific times, exposure time is determined by such factors as the time required to complete the assigned performance task(s). Even these relatively gross criteria have not been applied consistently, however, and the inability to do so stems primarily from the failure of researchers to agree upon just what constitutes an "extreme" or a "moderate" thermal environment. The problem is further complicated by the existence of such variables as degree of subject acclimatization (discussed under subject variables) which affects both physiological tolerance and the ability to perform. In general, conflicting reports on performance decrement are partly attributable to:

1. Treating exposure time as a dependent rather than an independent variable; i.e., allowing thermal conditions to dictate the length of time subjects remain and/or perform in a given situation. When subjects are unable to remain in one or more experimental conditions for the prescribed time, the resulting information on physiological tolerance, however valuable, is gained at the expense of losing performance data. An example of this type of loss occurred in the early work of Viteles & Smith (1946). Using tasks simulating the operations of naval plotting and chart room, they found no adverse performance effects at ET's of 75° and 80°. At ET 85°, performance decreased only slightly although Ss reported feelings of annoyance and marked discomfort. At 94° ET, "Marked irritability, dizziness, visual blackout and nausea became increasingly common (p. 107)"; none of the subjects were able to complete the tasks. Wing (1965) noted that "Physiological tolerance limits for men exposed to high ambient temperatures have been available for nearly two decades. It has long been suspected, however, that human performance deteriorates well before physiological limits have been reached (p. 960)." Experiments in which subjects are unable to complete the task(s) add little in the way of quantitative evidence to support this "suspicion."

2. Using equal exposure (tolerance) times as a basis for equating thermal conditions. Blockley & Lyman (1951), using temperatures of 160°, 200°, and 235°, RH 40%, found little effect on Ss' performance until 5-6 minutes prior to reaching their physiological tolerance limits. Pepler (1959), in a quasi-replication of the study found: "It was technically impossible to maintain the very high air temperatures and low humidity of Blockley and Lyman. It was decided, therefore, to use a humid climate which would impose a stress equivalent to their 200°F (93°C) condition, as assessed by the subjects' average tolerance times (p. 383)." The resultant "equivalent" conditions were 116°DB, 105°WB and 100 ft/min air movement. Pepler found that decrements in performance were much more severe, and occurred earlier in the testing session. The difference in results is not surprising in light of previous discussion of the components of thermal stress. There is at present no empirical data to suggest that either the qualitative or quantitative (subjective or physiological) stress effects of these different thermal conditions can be safely equated.

3. Assuming that equal exposure times allow thermal conditions of "equivalent warmth" to act with equal effect on performance. Wing (1965), plotting performance decrement (at various levels of effective temperature) against exposure times, commented on this problem:

> "Secondly, because the curve is plotted in terms of effective temperature, there is the danger of assuming that all the combinations of temperature, humidity and airspeed which yield a given effective temperature also produce the same degree of performance decrement. This is undoubtedly not the case. Eventually performance decrements should be separately determined for a large number of combinations of temperature, humidity and air movement and reported in a tri-dimensional chart. However, such voluminous data are not yet available...(p. 963)."

A final factor involved in selecting heat stress exposure times is the lack of reliable information regarding the effects of (1) repeated exposures to high temperatures, and (2) continuous exposure to mild or moderate thermal environments for periods of several months. Previous studies have controlled for such effects by random assignment of Ss to conditions. This technique is effective as long as the effects of thermal stress are assumed to be relatively transient and non-additive.

SUBJECT VARIABLES

A NUMBER OF studies such as that by Carlson (1961) indicate that the failure to conclusively demonstrate performance decrement under thermal stress is often due to extreme inter-subject variability. Carlson noted that: "Although each individual's performance was consistent, the range of performance among the nine subjects was too great to permit definitive analysis of the influences (of heat) on vigilance (p. 10)." This variability is the result of diverse physiological and psychological characteristics which each subject brings, in differing amounts, to the experimental situation. Under the assumptions of random sampling, these characteristics, such as age, physical condition, intelligence, etc., are assumed to be equally distributed among experimental and control groups. Frequently, however, this assumption is not met, and researchers have often been forced to use whatever subjects were at hand. The acquisition of subjects solely on the basis of availability, incidental sampling as Guilford (1957) terms it, has severely limited the generality of many experimental findings. Unfortunately, the conditions which lead to expediency in sampling are not likely to improve in the near future. For this reason, it is vital that the researcher be fully aware of the role played by subject variables in the determination of performance. Given a knowledge of the relevant variables, there is an increased probability that some controls can be applied, perhaps through modifications of the experimental design and procedures, to limit overall variability within groups.

PHYSIOLOGICAL FACTORS

ADAPTATION TO thermal stress involves changes in a number of physiological systems. For convenience, these changes are summarized in Table IV, prepared by Fox (1965).

TABLE V

ADAPTIVE CHANGES

Mechanism	Adaptation
Sweating	a. Increased capacity*
	b. Quicker onset*
	c. Better distribution over body surface*
	d. Reduced salt content*
Cardiovascular	a. Greater skin blood flow*
	b. Quicker response*
	c. Blood flow closer to skin surface
	d. Better distribution over body surface
	e. Reduction in counter-current blood vessels
Metabolic	a. Lowered Basal Metabolic Rate
	b. Lowered energy cost for a given task
Respiratory	a. Hyperventilation*
Heat Storage	a. Increased tolerance to higher body temperature
	b. A lower resting body temperature*
Behavioral	???

* Indicates adaptations for which there is agreement regarding experimental evidence gathered to date.

The magnitude, rate, and direction of change have been established for such physiological measures as heart rate, blood pressure, respiratory rate and volume, body temperature (oral and rectal) and rate of sweating. The relationship between changes in these measures and changes in environmental heat loads depends largely on the particular physiological mechanism examined. Thus, the correlation of thermal index values with evaporative sweat loss is high; with rate of sweating, it is low. Regardless of the size of the correlation coefficients, however, most researchers have continued to select levels of these physiological measures to operationally define thermal stress. In this definitional capacity they have been particularly useful in setting thermal tolerance limits for subject safety.

On the strength of their correlation with changes in the thermal environment, numerous attempts have been made to relate adaptive physiological changes to concurrent variations in performance. There is little argument among researchers that some kind of relationship exists, but specifying the parameters which control or mediate its effects has proven extremely difficult for a number of reasons:

1. Effects of physiological change vary with the type of performance being measured. Reliable decrements have most successfully been demonstrated for tasks requiring moderate-to-heavy physical exertion. In this situation, the expenditure of energy in performing places an additional drain on the already overworked physiological systems and thus increasingly augments the effects of the thermal stress already present. The picture is not nearly as clear with respect to effects of heat on complex mental and psychomotor performance since, as Pepler (1960) pointed out:

> "Little or nothing is known, however, of the mechanisms or causes underlying these effects. Changes in performance have been observed in the absence of (Watkins, 1956; Weiner & Hutchinson, 1945) or independently of (Mackworth, 1950; Pepler, 1958) changes in the concomitant physiological indices of an effect of warmth, such as body temperature, or the amount of weight lost as sweat (p. 68)."

2. Because changes in physiological measures and changes in performance have each been shown to correlate with exposure to high temperature, it has been assumed that they must also correlate with each other to the same extent. Empirical studies have found this assumption untenable for many complex performance tasks. Bell, et al. (1964), for example, reviewed the relation between one physiological response to heat (body temperature) and visual vigilance. They concluded that:

> "No consistent relation, however, has been shown in any of these studies between body temperature or changes in body temperature and changes in performance under adverse environmental conditions, except that a rise in deep body temperature and a deterioration in performance have both been shown to be related to the environmental temperature (p. 287)."

3. Prediction of performance decrement is relatively good at the upper limits of physiological adaptation; i.e., performance decreases rapidly once a subject begins to display symptoms of heat exhaustion or pyrexia. As Hendler (1964) summarized:

> "It is obvious that performance and behavior of the individual as an operating entity depends upon the functional status of the parts that comprise the whole. As indicated previously, exposure of the individual to environmental temperature extremes can result in a wide variety of compensatory changes, the overall effects of which can confidently be expected to result in performance decrement when the compensation is insufficient (p. 334)."

Short of this point, however, prediction is poor, and the actual shape of the curve representing performance change as a function of physiological adaptation is unknown.

ACCLIMATIZATION. A final factor which must be considered under physiological adaptation is that of acclimatization which can be broadly defined as the degree of efficiency of the individual's combined adaptive mechanisms in coping with environmental heat loads. More specifically, the classical picture of acclimatization is described by Fox (1965) as follows:

> "The main features are a less marked increase in heart rate while working, lower skin and deep body temperature, a greater production of sweat and, subjectively, a lessened sense of discomfort (p. 66)."

The following summary presents some important points to be considered in controlling for the effects of acclimatization in heat stress research:

1. Acclimatization represents a process of adaptation characterized by reduced physiological strain under thermal stress. It is operationally defined by specific physiological indices such as sweat rate, heart rate, rectal temperature, etc. As an aggregate of these separate measures, acclimatization is still subject to the limitations described previously for single physiological parameters; it is necessary in establishing physiological tolerance limits, but its utility in predicting performance decrement is best under conditions in which thermal stress approaches those limits.

2. In general, Ss should be acclimatized under the hottest of the experimental conditions planned. There is some evidence that adaptation across climatic conditions occurs, but the exact amount of transfer has not been established.

3. For studies interested in measuring performance decrement under some standard operational condition involving thermal stress, subjects should be brought to the maximum level of acclimatization possible for two reasons. First, in most field studies or studies simulating operational situations, the interest is primarily in determining the amount of performance degradation which occurs in spite of rather than in the absence of defenses against thermal stress. Thus, prospective studies of pilot performance might focus on the decrement which occurs even with standard ventilation, ad lib. water intake, and a subject who is fully acclimatized. Second, full acclimatization for Ss prior to performance testing avoids the type of confounding reported by Wilkinson, et al. (1964) in their study of heat effects on reaction time and auditory vigilance. They reported that "Results...confirm the development of heat acclimatization over the testing periods...(p. 289)." This situation should be avoided until such time as data linking change and/or rate of change of adaptation with performance becomes available.

4. All Ss should be exposed to the full acclimatization training program. A physical examination, however thorough, determines only the "normality" of a S's physiological adaptive systems; it does not insure that these systems will function adequately under extreme thermal loads. Gold (1961) has noted this problem:

> "The philosophy of judging heat tolerance usually takes the form of an "index" that seeks to express physiological 'strain' in terms of numbers. The greater the number, the greater the strain; the lesser the number, the lesser the strain. However, inherent in such a philosophy is the fallacy that the level of strain by itself can constitute an adequate evaluation of heat tolerance. At this laboratory it is felt that two questions must first be answered before heat performance can be properly evaluated. First, to what extent can an individual dissipate heat? Second, how great a price must he pay? Indexes of strain can at best answer only the second question, and, as such, information obtained from them is liable to be quite misleading (p. 144)."

CONCLUSION

IN PRESENTING A critical analysis of any body of experimental data there is always a danger of overemphasizing the negative aspects. In the case of thermal stress research there are many such aspects, the most obvious being the radically divergent conclusions regarding the effects of "heat" on performance. However, rather than dwelling on the fact that such a conflict exists, I have attempted instead to explain its genesis in terms of certain uncontrolled (or poorly controlled) environmental and subject variables. In conclusion, let me summarize the propositions emphasized in this paper:

1. There is a need to agree upon some measurement index whose units would allow "thermal stress" to be operationally defined from one experiment to another. It may be that a single such index is not possible due to differing situational requirements; the attempt, nevertheless, should be made.

2. It is time to question, experimentally, the assumption that human performance - under conditions of high ambient temperature and humidity - will remain "normal" as long as physiological adaptation is maintained. Blockley, et al., pointed out some time ago that:

> "...studies of unclothed men in relatively mild heat conditions, within the climatic range, have shown that the ability to perform even simple tasks is impaired long before the danger of physiological collapse is apparent. Basically, the assessment of body heat storage is predictive of the physiological tolerance of men; it is much more difficult to predict the way in which performance will be affected by the discomfort which accompanies even a perfect physiological adjustment to heat stress. Psychological considerations become of supreme importance in this mild heat area." [p. G-1] (italics mine)

3. The demands made on operators in modern man-machine systems are becoming increasingly complex. With respect to thermal stress, it is necessary not only to investigate the psychological considerations (motivation, learning, etc.) mentioned above, but to examine their effects on more complex types of performance involving such functions as perception, decision making, memory, etc.

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Studies on Subjective Assessment of Workload and Physiological Change of the Pilot During Let-Down, Approach and Landing

Squadron Leader A.N. Nicholson
Flight Lieutenant R.G. Borland

Royal Air Force Institute of Aviation Medicine,
Farnborough, Hampshire, United Kingdom.

and

Captain L.E. Hill

British Overseas Airways Corporation,
Hounslow, Middlesex, United Kingdom.

Subjective assessment of workload and changes in the rr interval and finger tremor of the pilot have been studied during the let-down, approach and landing of a Boeing 707 aircraft. The observations have been made during thirty-four landings into international airports.

Each let-down was assessed for its overall difficulty and with reference to the various factors which influence the work pattern. Each assessment was made by means of the 10 cm line technique. In the case of overall difficulty of the let-down the extremes of the assessment were "Extremely Difficult" and "No Difficulty" while in the individual factors the extremes were "Very Favourable" and "Very Unfavourable". The pilot was required to indicate his assessment by a single line crossing the 10 cm line and the assessment was quantified by the measurement of the intersection from the mid-point of the line. The individual factors influencing the let-down, approach and landing were:

a. Aircraft with reference to technical serviceability, efficiency of the crew and problems associated with the passengers.
b. The availability of navigational aids during the let-down, approach and landing.
c. The meteorological conditions with particular reference to ceiling and visibility, turbulence and conditions affecting the landing such as rain, snow and cross winds.
d. The physical features of the airport with regard to the length and condition of the runway, the lighting in the event of a night landing and the existence of high ground.
e. The efficiency of the control procedures with reference to the air traffic control, communications, traffic and tower.

The rr interval was recorded during the terminal part of cruise and the let-down and the finger tremor was recorded before take-off and within one minute of touch-down.

The physiological change in the pilot associated with an uneventful let-down was a mean rr interval between 400 and 450 msec and a finger tremor between 0.3 and 0.8 $msec^{-2}Hz^{-1}$ at the 10Hz frequency.

During let-downs in which poor control was often accompanied by inadequate aids and unfavourable meteorology and frequently preceded by a high workload cruise (indicated by a mean rr interval at end of cruise of less than 630 msec) the mean rr interval at touch-down was less than 400 msec but the finger tremor at 10Hz remained within the range for an uneventful let-down.

In the event of an unresolved problem persisting or a fresh problem of some magnitude appearing during the approach mean rr intervals of less than 400 msec were accompanied by finger tremors between 0.8 and 1.3 $msec^{-2}Hz^{-1}$ at the 10Hz frequency.

It is considered that mean rr interval around touch-down reflects the workload of the cruise, let-down, approach and landing whereas changes in finger tremor are associated with untoward events during the approach.

FULL PAPERS OF THE ABOVE HAVE BEEN PUBLISHED ELSEWHERE

7

OPERATIONAL MEASURES OF PILOT PERFORMANCE DURING FINAL APPROACH TO CARRIER LANDING

by

Clyde A. Brictson

Dunlap and Associates, Inc.

SUMMARY

Measures of pilot performance during night carrier landings were found to differ statistically and practically from daytime performance in terms of altitude control. Night approaches were characterized by more altitude variability, a larger percentage of approaches below glide slope and higher bolter rates compared with day approaches flown by the same pilots. Practical application of the performance data is discussed in terms of pilot and LSO training, visual landing aids and aviation safety. Empirical landing performance criteria are developed from the data and used to predict the probability of landing success as a function of deviations in final approach performance.

OPERATIONAL MEASURES OF PILOT PERFORMANCE DURING FINAL APPROACH TO CARRIER LANDING[1]

Clyde A. Brictson
Dunlap and Associates, Inc.

FINAL APPROACH TO landing has always been a critical phase of flight. Historically, the greatest number of aircraft accidents has occurred during final approach and landing (Eldridge, 1961). Change the landing field to an aircraft carrier deck, move the carrier through the water at 30 knots, oscillate the deck in three additional degrees of freedom simultaneously (pitch, roll, and heave), add a black night, and final approach to landing takes on dimensions unknown to land based pilots. In the fleet, pilots typically accomplish daytime carrier landing in routine fashion. At night, with an impoverished visual field, the landing accident rate increases four-fold.

PREVIOUS RESEARCH

A good deal of information about carrier landing performance has been reported in the last three years. The information was generated during a research project which developed a rationale to evaluate visual landing aids for night carrier recovery. The first project report (Winterberg, Brictson, & Wulfeck, 1964) analyzed the system in terms of its components and concluded that no objective measure existed to assess the quality of a final approach and landing. It also recommended that objective performance criteria be developed to evaluate the wide range of performance that exists between a successful and unsuccessful recovery. A second report (Brictson, 1966) described successful application of an objective measurement scheme to record day and night final approach performance and suggested that additional data be collected to serve as a basis for development of empirical landing performance criteria. A third report (Brictson, Hagen, & Wulfeck, 1967) documented pilot landing performance during combat operations in the Gulf of Tonkin.

THE CARRIER LANDING SYSTEM

We have defined the carrier landing system in terms of a carrier, aircraft, pilot, landing signal officer (LSO), and the environment in which the system operates. Carriers can be classed as either small or large; the length of the angled deck (landing platform) can range from 520' to 724' in length. There are, at present, seven different carrier-based aircraft types, each with its own slow speed handling and maneuverability characteristics. They range from small attack aircraft (A4) to fighters (F4, F8), bombers (A5, A6, A7) and "tankers" (A3). The pilots who fly the jets are characterized by different levels of experience in total flight hours and in number of day and night carrier landings. Pilot experience runs from initial carrier landing qualifications by so-called "nuggets" or inexperienced pilots to two tours of combat exposure with several hundred night recoveries by experienced pilots. The LSOs who monitor final approach performance can also be differentiated by varying amounts of experience. Finally, the environment in which the system operates is a function of weather...cloud cover, sea state, ceiling, visibility, wind-over-deck, and the availability and degree of visibility of such natural phenomena as the horizon, the sun, and the moon including its phase.

VISUAL CUES

Fundamental to effective carrier landing operations are the natural and artificial visual cues available to the pilot during final approach to recovery. During the day, under normal conditions, a pilot has an abundance of natural visual cues which provide information on the "goodness" of his final approach to landing. He uses the horizon and the aircraft nose geometry for attitude information and estimation of touchdown point; aircraft, ship, horizon geometry and surface texture of the sea with ship's wake for altitude control information; a three-dimensional view of the ship for additional relative altitude and speed of closure information; and the painted runway centerline for alignment information. Expansion patterns and peripheral streaming may also provide feedback on his final approach performance. The pilot's use of natural and artificial visual cues during final approach is discussed more fully in Winterberg, Brictson and Wulfeck (1964).

At night, in dark and somewhat hostile visual surroundings which at best deteriorate, and at worst eliminate, most natural visual cues, the pilot is forced to rely almost exclusively on artificial cues provided by visual landing aids. For example, the natural horizon may be unavailable up to 30 percent of the time; information from the surface texture of the sea or the ship's wake may be gone; and the three-dimensional view of the ship may be occluded by darkness. In the absence of those natural visual cues, the pilot uses information provided by visual landing aids. The Fresnel lens, which projects glide slope information in the form of a lighted "meatball" image, is used by the pilot to estimate his relative position on glide slope; centerline strobe lights and drop lights are used for lineup information; and the angle-of-attack index (inside the cockpit) is used for speed information. The pilot scans the visual field for feedback on the quality of his final approach performance, obtains information from the visual landing aids (and LSO), and makes appropriate control inputs to effect a safe recovery.

Visual landing aids are therefore a fundamental and a critical part of the carrier landing system. They provide the artificial visual cues that the pilot uses to judge the adequacy of his final approach performance...and they are especially critical at night.

What influence do day and night visual cues have on final approach performance? Does landing performance differ day and night? Can the differences be quantified? What happens to recovery performance when the deck is pitching? How does pilot experience influence landing performance? By measuring and statistically defining empirical samples of final approach performance, operational answers to those questions have been provided.

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Three years of human factors research on carrier landing system performance in day and night environments is synthesized and reviewed in this article.

METHOD

SUBJECTS. All subjects were U.S. Navy pilots drawn from fleet squadrons. They ranked from Ens. to Commander in each squadron sampled. Three levels of pilot experience were defined: inexperienced pilots, fleet experienced pilots and combat ready pilots. In the combat sample 105 pilots averaged slightly over 100 combat missions with an average across squadrons of 282 carrier landings. A characteristic profile of fleet experienced pilots is reflected by F4 pilot background data showing that the typical pilot averaged 72 day and 22 night carrier landings in the F4 aircraft. Inexperienced pilots, as reflected by F8 pilots, had no previous carrier landing experience in that type aircraft.

SAMPLE SIZE. A total of 1876 final approaches were recorded across six types of jet aircraft. The total is broken down into 1268 day and 608 night landings which were obtained during five data collection tours aboard four aircraft carriers. The F4 sample, which is used most extensively to illustrate approach performance trends, is based on 136 day and 83 night approaches collected aboard two attack aircraft carriers. Combat landing operations described later are based on 912 day and 390 night approaches aboard one carrier operating off North Vietnam.

SYSTEM VARIABLES. All performance data were collected aboard large so-called super carriers and included the USS Kitty Hawk, USS Constellation, USS Enterprise and USS Ranger. A3, A4, A5, A6, F4 and F8 jet aircraft were used for data collection. Visual landing aids included: the Fresnel lens optical landing aid (line and point stabilized); centerline strobe lights and drop lights; and white and red floodlights. Weather conditions, except where noted (pitching deck), were considered relatively ideal; calm sea, visible horizon, and acceptable ceiling and visibility.

INSTRUMENTATION. The procedure for recording final approach performance has been described by Brictson (1966). It consisted of a shipboard instrumentation system (SPN-10) which recorded in-flight geometry of aircraft during final approach to landing. Twin precision radars locked on and tracked the aircraft. The data were processed through a signal data recorder which provided up to eight channels of continuous flight information. The tracking radar was calibrated against a known standard prior to shipboard recording and was checked periodically throughout the operations at sea. In a technical description of the system, Shuh, Rupp and Ames (1962) reported the radar range error as 4 feet and angular error as 0.3 milliradians. The signal data recorder was a military version of an eight channel Offner dynograph and provided a continuous curvilinear electric record of aircraft final approach variables. Recorder calibration was performed prior to data collection and the calibration for each channel was checked before each landing sequence. A paper take-up speed of 5 mm. per second was maintained for all recordings. Range, true altitude, altitude error, lateral error, sink speed, true air speed, deck pitch and closing speed were the variables usually recorded.

RESULTS

MEASURES OF APPROACH PERFORMANCE. Measures of day and night carrier approach performance included the following system variables:

- Altitude Error from Glide Slope
- Lateral Error from Centerline
- Sink Speed at the Ramp
- Approach Speed at the Ramp
- Arrestment Wire
- Boarding Rate
- Bolter Rate

ALTITUDE ERROR. Measures of altitude error from a prescribed final approach glide slope of 3.5° were taken at four ranges from touchdown. Day and night altitude error envelopes are illustrated in Figure 1. The envelope dimensions are defined by ±2 standard deviations from mean performance for successful recoveries.

In comparing day and night altitude error performance several things seem clear. First of all, greater variability was found in control of altitude error at night. Night approaches show increased altitude performance dispersion at each range from touchdown.

Previously published results (Brictson, 1966) reported statistically significant differences between day and night altitude control at ¼ ($p < .01$) and 1/8 ($p < .05$) miles from touchdown. Furthermore, pilots also were found to be relatively consistent in their day and night altitude performance as reflected by reliability correlations. At the ramp, altitude performance correlated .78 by day and .21 at night.

Second, a greater percentage of aircraft flew below glide slope at night than during the day recoveries. At night, 30% of the F4s were below glide slope at 1/8 mile from touchdown; during the day, with the same pilot sample, only 9 percent approached below glide slope. The tendency to fly below glide slope with greater frequency at night has been found in other data samples as well and is illustrated in Figure 2.

Finally, the night bolter rate (touching the deck without arrestment) was found to be approximately double the day rate for F4 aircraft. Pilots had a greater tendency to land farther up the deck at night and consequently had higher bolter rates compared to their day approaches (see Figure 5).

In summary, night altitude control performance was found to differ statistically and practically from daytime performance. Night approaches were characterized by more altitude variability, a larger percentage of approaches below glide slope and higher bolter rates compared with day approaches flown by the same pilots.

LATERAL ERROR. Lateral error from centerline was also measured at four ranges from touchdown. Mean performance ±2 standard deviations for successful recoveries are shown in Figure 3. Reliability correlations for pilot lateral error at the ramp were .75 day and

.69 night which reflect a relative consistency in performance. No practical or statistical differences were found in day and night lateral error. F4 lateral error performance was found to be essentially the same for both day and night final approaches.

OTHER PERFORMANCE MEASURES. Sink speed or vertical speed was measured at the ramp just prior to touchdown. Data from a study of combat landing operations are graphically displayed in Figure 4. For five different jet aircraft covering over 1300 day and night approaches, no significant or practical differences were found between day and night sink speeds.

Final approach airspeed was recorded at the ramp for the same jet aircraft during recovery operations following combat sorties. The data were analyzed and no practical or statistically significant differences were found between day and night approach speeds.

Day and night wire arrestment data for F4 aircraft were calculated and evaluated for trend information. With four wires available to arrest approaching aircraft there was a tendency for a greater percentage of aircraft to land shorter (#1 and #2 wires) by day and longer (#3 and #4 wires plus more bolters) by night (see Figure 5).

APPROACH PERFORMANCE UNDER PITCHING DECKS. Fleet doctrine calls for pilots to fly a constant glide slope during final approach and this is especially stressed when seas are high and the carrier deck is pitching. What are the operational consequences of a pitching deck? During one data collection trip, heavy seas causing considerable deck motion provided the opportunity to record approach performance under a pitching deck condition.

A pitching deck was operationally defined as deck motion that exceeded ±4 feet (deck up or down) from a stable platform. Thus, high deck pitch was defined as any deck movement which exceeded four feet either up or down. Low deck pitch was deck movement less than four feet.

Effects of high and low deck pitch on day and night approaches are shown in Figure 6 which compares landing effectiveness by contrasting the percentage of unsuccessful approaches under low and under high deck pitch conditions. Seventy percent of the night recoveries under high deck pitch were unsuccessful (bolters or wave offs). In sharp contrast only 18% of the day approaches were unsuccessful under high deck pitch.

Previous data indicates that during the day under calm seas, pilots fly consistently above glide slope. When the deck is pitching they tend to fly even higher. At night, when the pilot is apparently unable to perceive deck motion, the percentage of unsuccessful approaches was found to increase more radically (18% to 70%) than with any other day/night recovery condition recorded to date.

INITIAL CARRIER APPROACH PERFORMANCE. How do pilots perform during their first attempts to land aboard an aircraft carrier? To answer this question, data were collected on a small sample (N = 58 night; 23 day) of F8 replacement pilots. Again, primary interest was focussed on the variability of altitude error control performance -- in this case for pilots making their initial carrier landings at sea.

A summary of day and night altitude error performance at three ranges from touchdown is presented in Figure 7. Performance data were grouped and used to develop altitude performance envelopes. Day and night envelopes were based only on approaches which resulted in successful landings with the dimensions defined by mean altitude error ±2 standard deviations.

In interpreting the envelope dimensions it is useful to recall the F4 data from Figure 1. Notice that night altitude error dimensions for "inexperienced" F8 pilots are approximately the same as those for "experienced" F4 pilots (Figure 1). Although different aircraft types should not be compared directly because of obvious differences in handling and maneuverability characteristics, it appears that with experience, pilots are able to reduce the variability of day altitude performance. On the other hand, night altitude variability, especially in the critical region below glide slope, remains almost constant regardless of experience. The relative frequency of low night approaches also appears to be consistent across aircraft types regardless of pilot experience.

The percentage of F8 aircraft below glide slope at 1/8 mile was 38% at night compared to only 19% by day. In general, at night as the percentage of F8 aircraft below glide slope increased, unsuccessful approaches (bolters, wave offs) increased and overall boarding rate decreased.

EMPIRICAL PERFORMANCE CRITERIA. How high or low, left or right, can an aircraft be at various ranges from touchdown and still land successfully? To answer that question data for successful carrier approaches, e.g., those that resulted in safe arrestment aboard ship, were used to develop performance envelopes in both vertical (altitude) and horizontal (lateral) dimensions. The dimensions of the performance envelopes were defined by $\pm 1\sigma$ (68%) and $\pm 2\sigma$ (95%) values from mean performance. Separate envelopes were developed for both day and night successful approaches. Figure 8 compares F4 day and night criterion envelopes ($m \pm 2\sigma$).

Those envelopes constitute empirical performance criteria. They are based on successful F4 landings aboard large carriers, by experienced pilots, under relatively good environmental conditions (calm seas, good visibility, distinct horizon, steady deck).

The altitude performance envelope for the F4 is illustrated and compared with the Fresnel lens ideal altitude tolerances in Figure 9. In reality, very few aircraft (<5%) fly within the restricted Fresnel criterion envelope.

PROBABILITY OF SUCCESSFUL RECOVERY. What happens if aircraft exceed the empirical performance criteria? What difference does it make in terms of landing success if an aircraft approach falls outside the $\pm 2\sigma$ envelope? To examine the predictive utility of the empirically derived performance envelopes "unsuccessful" approaches were superimposed on the "successful" performance envelopes. Both $\pm 1\sigma$ (68%) and $\pm 2\sigma$ (95%) envelopes are shown in Figure 10. A range

of 1/8 mile from touchdown was selected as a critical point at which an aircraft should be firmly established on glide slope, line-up and speed to land safely. One-eighth mile is approximately eight seconds from touchdown in an F4 aircraft. From the resulting scatter plots, the probability of successful recovery for extreme performance deviations (>2σ) was determined.

The probability of successful recovery, if an aircraft approached outside the ±2σ empirical envelope, is shown in Figure 11. During the day, with experienced pilots, there was a high probability of landing success if an aircraft approach was outside the empirical envelope. In fact, in our data sample all F4s which approached outside the criterion envelope landed successfully. At night, however, landing success for final approaches outside the criterion envelopes was only 45 percent for F4 and 55 percent for A4 approaches....In both aircraft, experienced pilots were at the throttle. For inexperienced pilots (F8), night landing success was only 19% compared with 38% by day. Lower boarding rates for F8 carqual pilots probably reflects more stringent approach tolerances, i.e., more technique waveoffs applied by LSOs, as well as less pilot proficiency in salvaging "poor" (>2σ) approaches. The practical consequences of exceeding the empirical criteria are obvious. At night, fewer approaches result in successful landings if aircraft exceed empirically derived performance criteria.

DISCUSSION

We have seen that the major difference between day and night carrier approach performance was found in altitude error control. At night, with an impoverished visual field, final approach performance showed more altitude variability, a greater percentage of aircraft below glide slope, higher bolter rates, and most significant, less landing success as measured by overall boarding rate. At night, altitude information during final approach to carrier landing is provided by the Fresnel lens optical landing system.

No one can guarantee that night landing performance can be improved. It may be as good now as it ever will be. The data reported here, however, strongly suggest that the greatest payoff in improving night landing performance lies in providing better altitude control information. We now have clearcut, objective evidence of where to place the emphasis in future visual landing aid design.

Just as no one can guarantee improved night performance so no one can guarantee fewer night landing accidents. The present accident ratio of approximately 4:1 (night vs. day) may be as low as we can expect given the interactions and complexities of the present system variables. The landing performance data do not necessarily portend any reduction in the existing carrier landing accident rate. Night approaches are more difficult than routine day approaches, simply because, as many pilots put it, "At night, it's dark. You can't see." Throw in a black, moonless night, no horizon, low fuel state...and the probability of a successful recovery rapidly diminishes. Under such conditions the landing accident potential increases as deviations in landing performance increase. With less than optimal conditions (pitching deck, carrier qualifications) the number of unsuccessful approaches begins to increase and the boarding rate drops. The overall effectiveness of carrier landing system performance is sharply reduced.

The fundamental question to be addressed, however, is whether existing night approach performance — with its increased altitude control variability, increased percentage of low approaches, and higher bolter rates — is acceptable system performance. If it is not, then major emphasis must be placed on improving the presentation, reliability and stability of height guidance visual cues in existing and future visual landing aids. One such system now under development by the Navy is CLASS (carrier landing aid stabilization system). More sensitive and precise visual information must be provided to the pilot to reduce his altitude performance variability during night carrier approaches.

We now have empirical quantitative measures of carrier landing performance utilizing the Fresnel lens optical landing system. Unfortunately, such objective data were not available during fleet evaluation of the Fresnel lens. Similar empirical data on landing performance based on new or modified visual landing aids are essential. Comparisons can then be made to the baseline performance data reported here to provide a basis for evaluating visual landing aids in terms of statistical distributions through measures of accuracy (η) and precision (σ) of final approach performance under a given set of conditions.

Along the way to collecting objective performance data to evaluate visual landing aids, several fall-outs have occurred. In the search for a criterion to assess the influence of system components on landing performance, empirical performance criteria were developed. Their practical implications were illustrated by describing carrier landing success in terms of how high or low, left or right, an approach can be and still result in successful recovery. Night approaches outside empirically developed envelopes were seen to represent potential accidents because of their extreme deviation (>±2σ) from mean approach performance. Based on the likelihood of successful landing, those approaches place a pilot "in extremis" and become calculated risks. At night, 1/8 mile from touchdown, landing success for F4 approaches outside the empirical envelope was 45%. Landing success inside the envelope was 86%. Which approach would you prefer?

The usefulness of landing performance data continues to expand. Currently, the objective measures are being used in training Landing Signal Officers (LSO) and as a training feedback device for pilots and LSOs after initial carrier landing qualifications and actual fleet exercises. A graphic presentation of final approach performance data is used to illustrate to the pilot his actual approach performance in terms of several continuously recorded variables. LSOs, on the other hand, have used the data as a reliable check on their own proficiency in monitoring carrier approaches. In addition, the empirical performance criteria can be used to validate flight training school measures and provide operational feedback to training personnel on the relative performance of fleet pilots.

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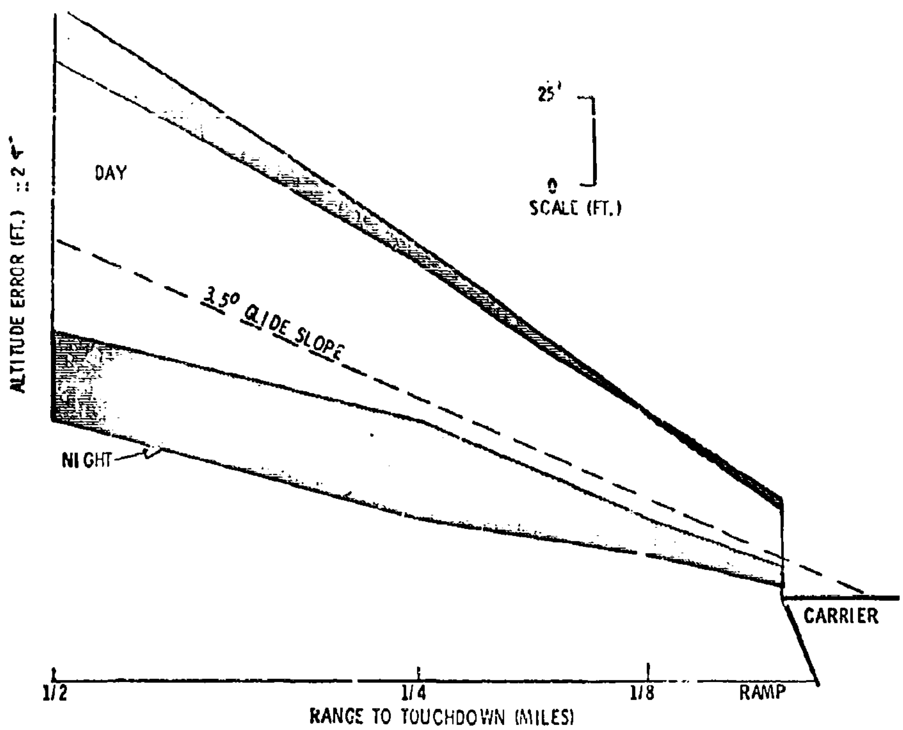

Figure 1 F4 day and night altitude error envelopes ($m \pm 2\sigma$)

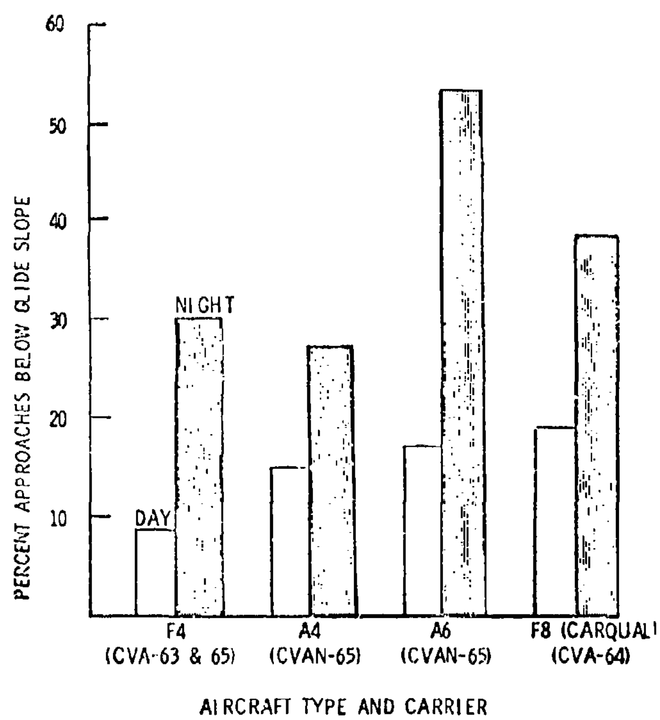

Figure 2 Percentage of aircraft below glide slope for day and night approaches at 1/8 mile

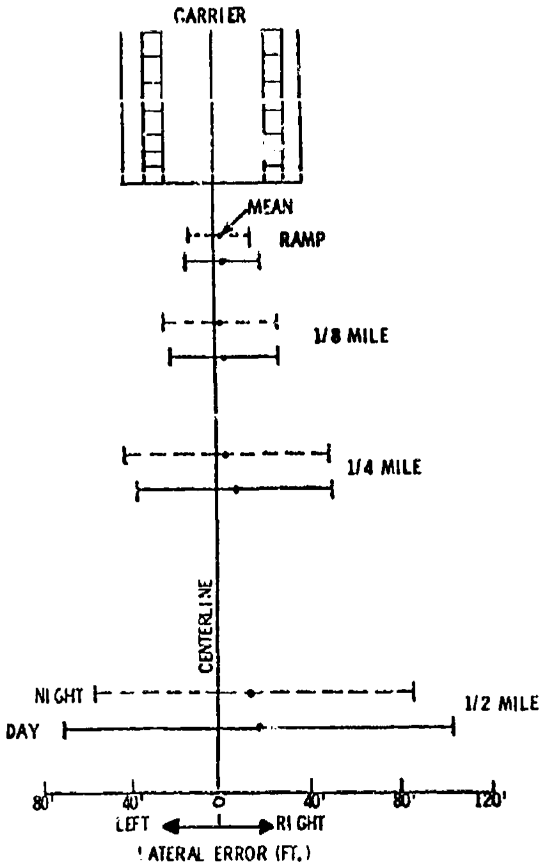

Figure 3 F4 day and night lateral error from centerline (m±2σ)

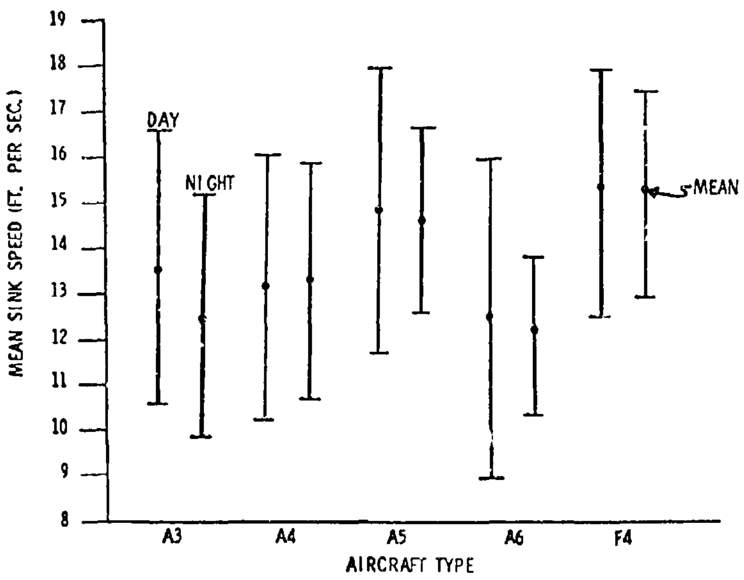

Figure 4 Comparison of sink speed means ±1σ as measured at the ramp for five jet aircraft during day and night approaches

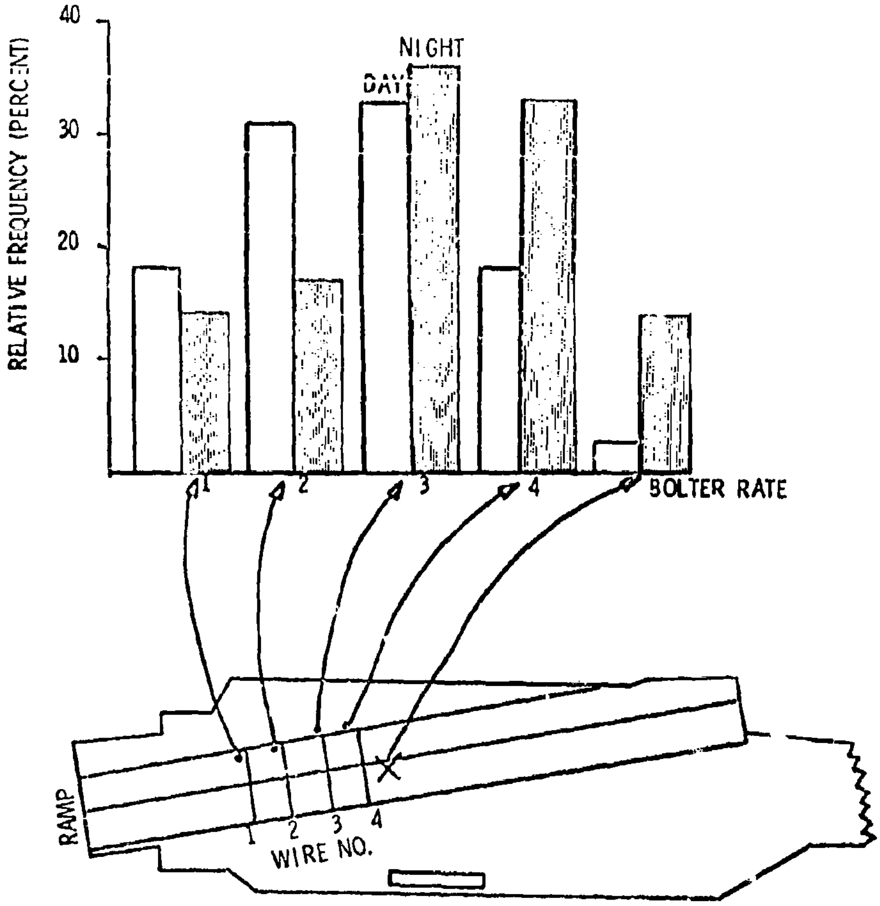

Figure 5 Day and night comparison of F4 wire arrestment and bolter rate

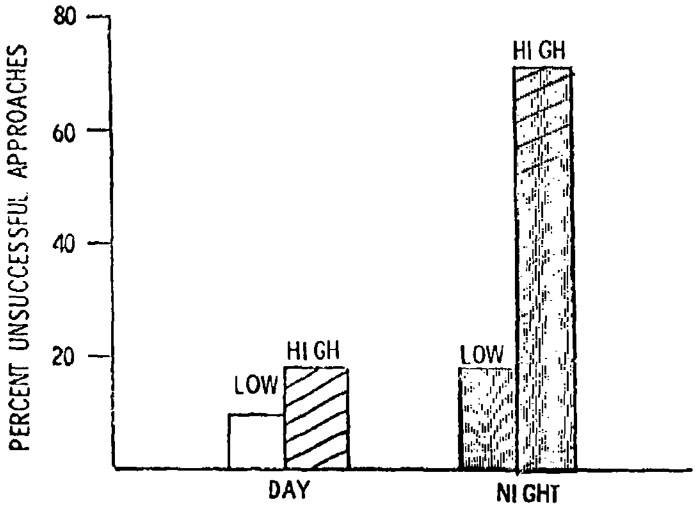

Figure 6 Percentage of F4 unsuccessful approaches day and night, during high and low deck pitch

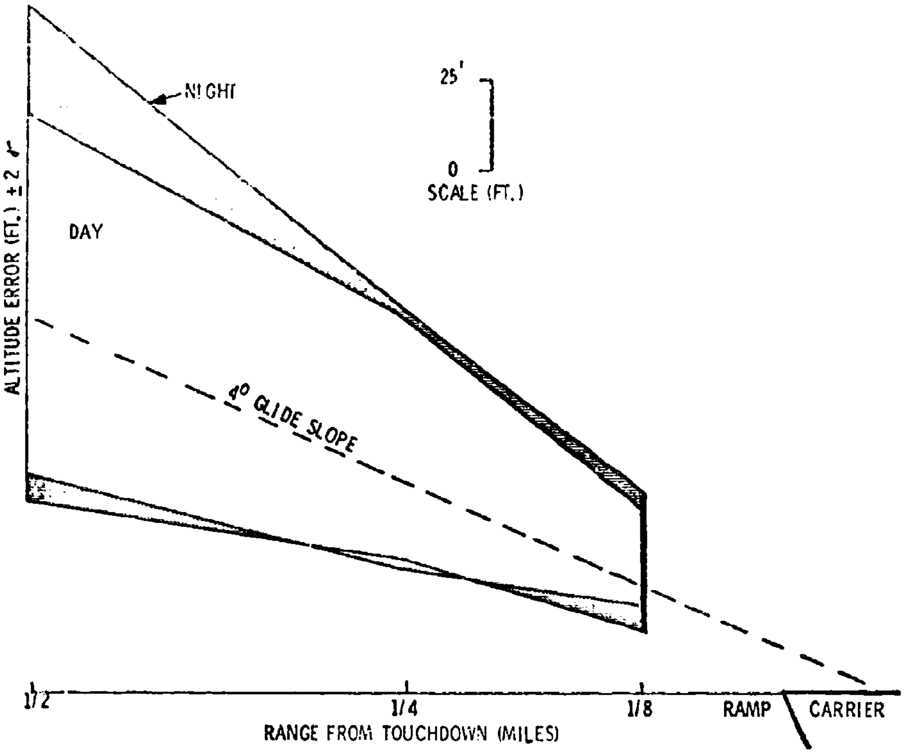

Figure 7 Day and night altitude error envelopes for F8 aircraft during initial carrier qualifications

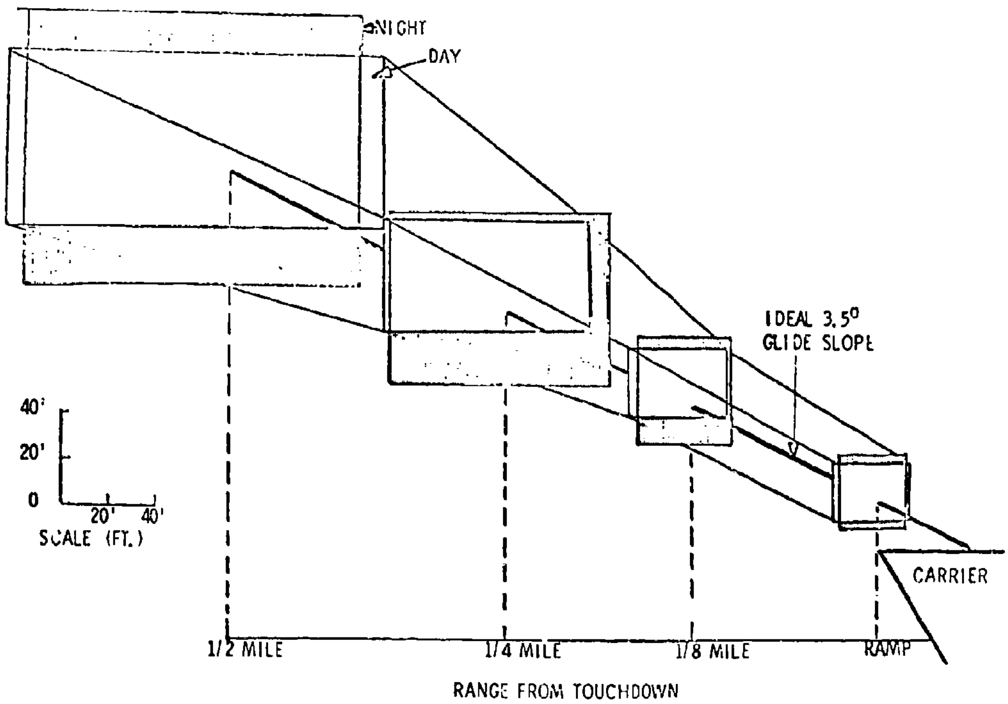

Figure 8 F4 day and night empirical performance envelopes

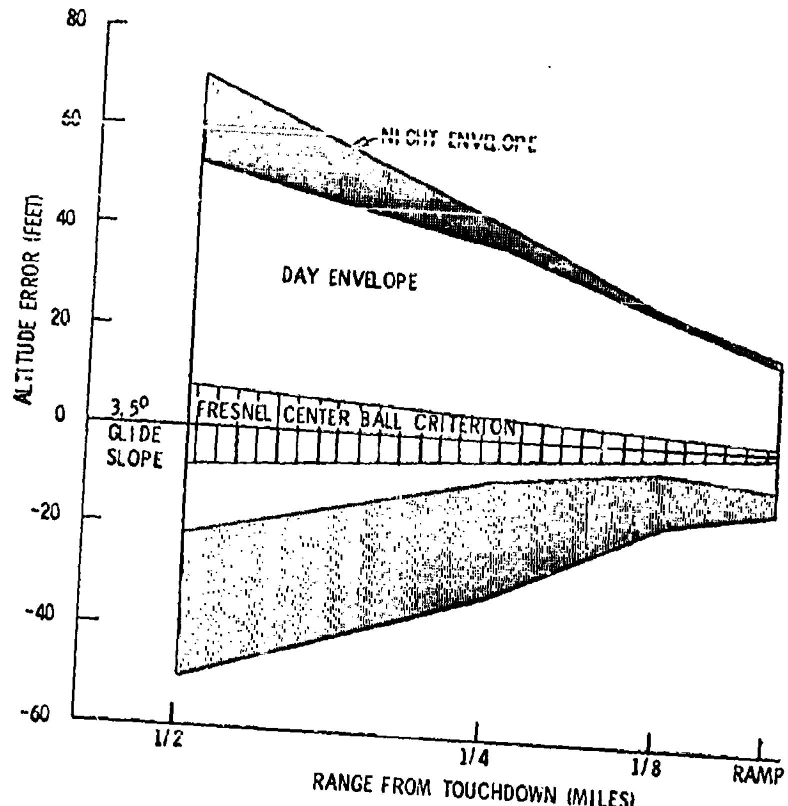

Figure 9 Day and night F4 altitude error envelopes ($\pm 2\sigma$) compared with Fresnel lens

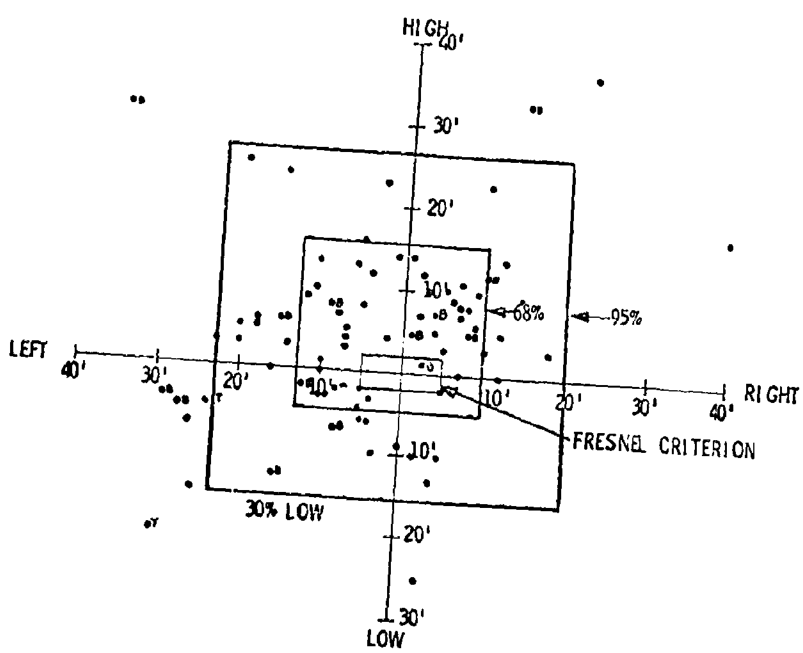

Figure 10 F4 night criterion envelopes (B = Bolter, T = Technique wave-off, N = 85)

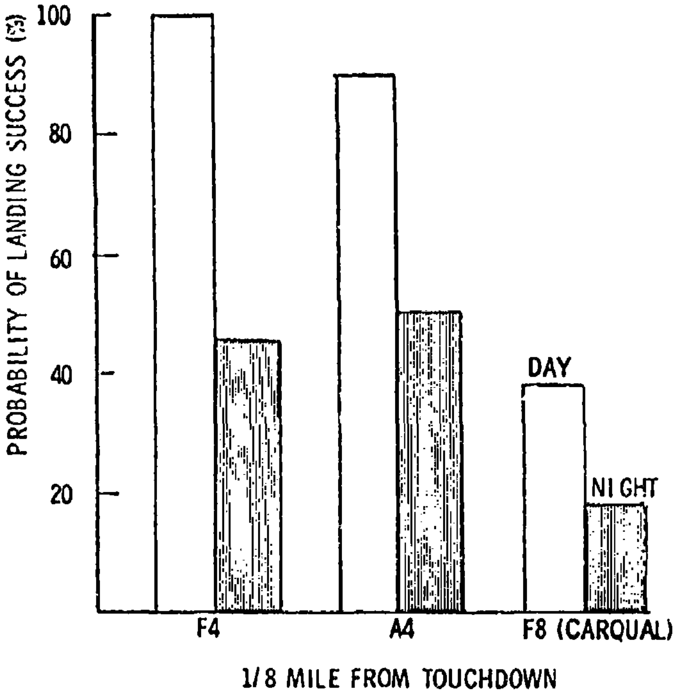

Figure 11 Comparison of day and night landing success when empirical criteria are exceeded

AIRCREW TASK LOADING IN
THE BOEING MULTIMISSION SIMULATOR

L. P. Zaitzeff
Military Airplane Systems Division
The Boeing Company
Seattle, Washington

SUMMARY

The Boeing Company's new multimission simulator, combining a 160° "real-world" visual display in high-resolution color, together with a completely functional and correlated cockpit, is described. The simulator permits aircrews to train in proposed aircraft and avionics systems and fly real-time missions over specially designated areas of the United States. The simulator was designed to evaluate aircrew performance using state-of-the-art concepts, controls, and displays incorporated in the cockpit of an advanced fighter/attack aircraft.

Visual target acquisition performance was used as a measure of task loading in tests of one- and two-man crews flying both realistically task-loaded missions and sequences requiring visual target acquisition only. Visual target acquisition performance of two-man crews was significantly better than that of one-man crews in both types of flights.

The Boeing Company has developed a research facility for evaluating aircrew performance in proposed aircraft with integrated avionics subsystems. This facility is the Boeing Multimission Simulator.

The simulator incorporates advanced aircraft designs with state-of-the-art avionics, displays and controls. New aircraft performance requirements are established, airframe models are tested in wind tunnels, and the final flight dynamics are programmed into a high-speed hybrid computer. Terrain elevation data from Army Map Service computer tapes are fed into the computer memory bank so that flight can be simulated over designated portions of the United States.

Integrated in the flight deck are interchangeable avionics displays and controls. The hardware portions of the avionics, film readers, and flying spot scanners are housed under the flight deck. The displays are driven by the hybrid computer logic in response to aircrew control settings.

The capabilities of the Multimission Simulator as presently configured are:

(1) Low-level, high-speed flight

(2) Terrain following and terrain avoidance

(3) Radar navigation

(4) Ground attack

(5) Air-to-air combat

(6) Flight controls/sensor displays evaluation

(7) Defense displays evaluation (ECM and missile threat)

(8) VFR target acquisition

(9) Data recording and reduction

(10) Stimulus material playback

The simulator flight deck incorporates the controls for two major systems. These are composed of:

(1) The major airframe subsystems

a. Flight controls

b. Flight and engine instruments

c. Propulsion

d. Landing gear

e. Hydraulics

f. Electrical power

g. Fuel

h. Life support

and

(2) The major avionics subsystems

a. Integrated communication, navigation (radio), and identification

b. Integrated navigation (doppler, inertial, LORAN, OARS, digital computer)

c. Multimission radar

d. Weapons control

e. Displays (HUD, VSD, HSD, radar repeater)

f. Integrated self-test and checkout

The simulator operates under two separate flight conditions - a VFR mode simulating flight under Visual Meteorological Conditions, and an IFR mode simulating flight under Instrument Meteorological Conditions.

In the VFR mode, the primary display is a 15-ft. radius screen upon which is projected high-resolution color motion pictures of low-altitude, high-speed flight over standardized flight corridors. A realistic, external field-of-view extends 160° laterally by 60° vertically. In VFR missions, the flight dynamics of the simulator are controlled by the Automatic Flight Control System operating in the Automatic Terrain Following mode; the flight path of the simulator is determined by the autonavigation system in conjunction with preset checkpoints along the test course. In the IFR mode, the pilot can control his own flight path within a 25-mile wide corridor assigned for his mission.

The aircrew can operate the simulator systems in real-time under normal, degraded mode, or emergency conditions. Complete missions can be programmed to include enemy ground defenses and air threats, and sensor and aircraft systems failures.

During the course of the missions, the hybrid computer monitors and records the crew operating procedures. Time of switch actuations, navigation update errors, and weapon delivery errors are typed out by the computer; actual flight profiles and systems parameters are traced out in analog graphics. A closed circuit TV system monitors crew actions and records the missions on video tape; aircrew communications are recorded on FM tape. In addition, direct observation of the aircrews is possible from an enclosed experimenter's balcony and control station.

The complexity of the Multimission Simulator requires rigorous training for the individuals who fly it. Operating and training manuals have

been prepared for use with the simulator. Display and control mockups are used as teaching aids in the ground school. Cockpit checkouts, familiarization flights, and training missions are conducted prior to scheduled tests. Selection can be made from complete sets of reference material to establish controlled briefings for selected missions. Complete cartographic, reconnaissance photography, and air intelligence information is available. Psychological set can be established by briefings of hypothetical strategic and tactical situations.

The Multimission Simulator is a flexible research tool. Studies have been conducted in target acquisition, aircrew utilization, cockpit geometry, task-load analysis, avionics displays and controls analysis. The studies have used military operational pilots, pilot-qualified Boeing personnel, and selected Boeing professional personnel.

The results of studies conducted in the Multimission Simulator show that task loading and performance are interrelated and depend on experience, training, equipment, and specific test instructions. Task loading is the utilization of an aircrew's mental and physical energies in the performance of tasks necessary for the successful completion of a mission. Task loading is generated by the individual aircrew's effort to accomplish that mission with the available airborne systems. A direct quantitative measure of task loading is difficult. However, an important end product of work load is performance within the mission. Thus, aircrew performance can be measured for mission subtasks under different conditions, and the most favorable work load conditions can be related to favorable mission performance.

In several Boeing tests, visual target acquisition, an important mission success parameter, has been used as a measure of task loading. In studies involving team efforts, it was found that two-man crews acquired prebriefed targets at significantly greater ranges than one-man crews. In missions where the only task was target acquisition, two-man teams acquired targets at 20 percent greater ground ranges than one-man crews. In missions where realistic flight management tasks were imposed on the crew, two-man crews acquired targets at 30 percent greater ground ranges than one-man crews. In both types of mission, visual target acquisition was stressed as the primary objective of the mission.

Figures 1 and 2 are examples of visual target acquisition comparing one- and two-man crew performance on two specific targets.

The sharing of the target acquisition load by two-man crews resulted in significant improvement in visual target acquisition performance. The exact reasons for the superior performance, however, are not known. Studies are planned to establish those critical areas wherein two-man task loading differs from that of the one-man.

Points of interest are that two-man crews apparently made better use of the preflight briefing materials. In flight, the observers' performance of routine tasks, allowed the pilots more time for critical mission objectives. Approaching target areas, the observers helped the team effort by referring to in-flight reference materials while the pilots were able to direct their attention outside of the cockpit. The observers also pointed out upcoming checkpoints and target features. Although the observers were unable to actually trigger the acquisition response to a target, they helped in confirming possible targets and rejecting false targets.

Generally, the two-man crews made fewer mistakes in standard operating procedures than the one-man crews apparently due to the more specialized nature of each crewman's duties, and the assistance afforded the pilot by the observer in calling out necessary requirements at proper times. There were some two-man conflicts generated by inadequate meshing of the crew's workload. However, these were generally resolved with training and experience. The conclusion was that two-man problems were outweighed by their overall improved performance.

There are many other areas which are suitable for investigation with the Multimission Simulator. The prime one is the analysis of improvement of mission performance through (1) improved sensor and predesignation displays, (2) the display of reference materials in flight, and (3) the optimal allocation of task loading between the pilot, his avionics, and crew.

Target acquisition performance has been used to determine the relative degree of task-loading between one- and two-man crews. The two-man configuration is considered more desirable because of significantly improved mission performance.

It is felt that an adequate analysis of mission performance requires a realistic and real time analysis of aircrew task loading. The Boeing Multimission Simulator provides this capability and has been a useful tool in the study of task loading and mission performance. By using the simulator, performance can be effectively improved through

(1) Proper systems and equipment design

(2) Training

(3) Proper crew utilization

(4) Confidence induced by systems reliability and accuracy

(5) Experience.

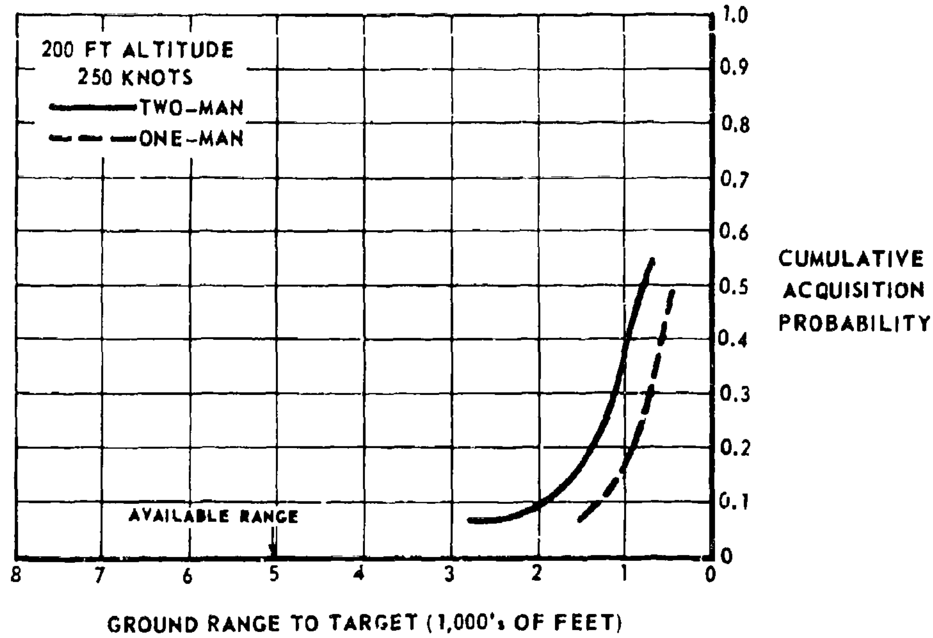

Figure 1. Comparison of One- and Two-man Crews. Visual Target Acquisition Performance Curves Combining Mission-Loaded and Acquisition Only Sequences. Target Radar Van.

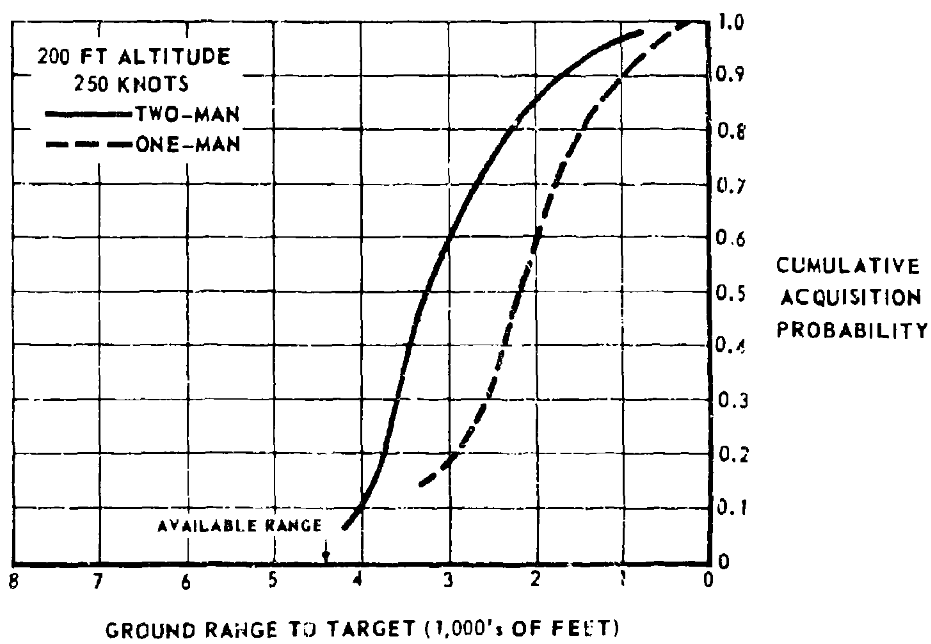

Figure 2. Comparison of One- and Two-man Crews. Visual Target Acquisition Performance Curves Combining Mission-Loaded and Acquisition Only Sequences. Target Oil Storage Tanks.

PHYSIOLOGICAL ASSESSMENT OF PILOT STRESS DURING LANDING

by

K. G. Corkindale and F. G. Cumming

Human Factors Group
Royal Aircraft Establishment
Farnborough, Hants.

and

A. M. Hammerton-Fraser

RAF Institute of Aviation Medicine
Farnborough, Hants

PHYSIOLOGICAL ASSESSMENT OF PILOT STRESS DURING LANDING

K. G. Corkindale, F. G. Cumming, MBE, and A. M. Hammerton-Fraser

1. WHEN IN 1965 it was decided to investigate the value of physiological measures of pilot stress during landing, a joint programme between the RAF Institute of Aviation Medicine and the Royal Aircraft Establishment was agreed, starting with a study of compensatory tracking on a digital display under laboratory conditions (1).

As a result of the encouraging results obtained from this investigation it was decided that the feasibility of the techniques used should be studied in the real flight situation, and to use as this flight situation trials being conducted at the Royal Aircraft Establishment, Bedford, by the Blind Landing Experimental Unit (BLEU) with the hope that the physiological measures could be used to augment the objective and subjective assessments of performance.

A physiological recording system had to be developed for this trial, suitable for installation in a fairly large aircraft. Basically, the system reduced a set of physiological measurements into cumulative digital form which were photographically recorded at ten second intervals. The measurements taken being:-

a) integrated arm muscle activity.
b) integrated leg muscle activity.
c) skin resistance activity.
d) respiratory rate.
e) respiratory flow.
f) end tidal carbon dioxide.
g) heart rate.

This set of measurements was the same as that used by Benson et al (1) in the early laboratory series with the omission of respiratory peak flow. A full description of the equipment is given by Hammerton-Fraser (2).

After testing in laboratory conditions the system was transferred to a rack in the forward passenger cabin of a Comet jet transport aircraft at BLEU, Bedford.

The reason why the Comet was chosen was that the programme being undertaken by the Blind Landing Experimental Unit at that time involved landing with or without Autoland facilities either completely blind or in various degrees of fog conditions and it was felt that this particular exercise should give as reasonable stressful a situation as one could possibly hope for in an early investigation.

2. THE EXPERIMENTAL PROGRAMME

Initial flight tests showed that the carbon dioxide recording equipment would not work satisfactorily at that time under the airborne conditions and eventually it was decided that this measurement would be abandoned. However, after successful flight testing of the remainder of the system a series of nine sorties was completed in February 1967 in which recordings were made on the back of the aircraft flight programme.

Initial analysis of the data from these runs undertaken while the aircraft was grounded for modification led to the conclusion that with only four subjects available for this experiment it would be difficult to make any valid deductions from the physiological measurements unless they were made in a statistically balanced programme of flights.

The reason why such a controlled programme was required was that it had become apparent from inspection of the initial ground and airborne recordings that there was a basal decline in the subjects level of physiological arousal in activity from the beginning to the end of flights of the duration intended. This flight duration of some 90 minutes was due to the operational use of the aircraft and it was clear that unless this effect could be balanced out by varying the order of different types of approach within each flight misleading conclusions might be drawn from this data.

A balanced programme of 16 flights comparing two conditions of visibility (fog screens, and clear) and two control conditions (head-up or head-down display of information) was designed (Table 1) and this programme commenced in July 1967. In the event owing to problems of aircraft availability only 9 flights were completed before the equipment had to be removed. Only data obtained during these 9 flights will be considered in this paper.

In summary, this programme had two main aims:-

1) to investigate the feasibility of obtaining records of a pilot's physiological activity in flight under operational rather than experimental conditions.

2) to determine the usefulness of physiological recording in the assessment of pilot work load.

3. EXPERIMENTAL METHOD

(i) FLIGHT PATTERN. The aircraft normally took off at maximum landing weight so it was able

to go straight into the circuit pattern. This usually permitted 8 approaches to be made including the final landing. Each circuit from take-off to touch-down took approximately 10 minutes, circuit height being 1500 feet.

The types of approach being studied by BLEU included full autoland, with the pilot acting purely as a monitor; manual instrument approach using head-up or head-down displays with and without auto-throttle. The head-up display was of a pure director type.

These manoeuvres could all be carried out either under clear screen conditions or with fog screens simulating visibility ranges down to Category 3 conditions.

During the early airborne series of runs physiological recordings were taken from the end of the downwind leg through touchdown into the overshoot phase. From these readings it became apparent, as might have been expected, that the most marked and consistent changes in physiological activity occurred during the last 2 minutes prior to touchdown; therefore in the balanced series of 9 flights recordings were only taken over this 2 minute period.

TABLE 1. PHYSIOLOGICAL ASSESSMENT OF PILOT STRESS DURING LANDING EXPERIMENTAL DESIGN

REQUIREMENTS

(i) No subject should perform two flights in one day.

(ii) Flights in each set should be completed before those in the next set are started.

(iii) In each flight circuit 1 should be autoland with fog screens. Circuits 2 to 6 should then be recorded as shown. If any of the required approaches is not completed it should be repeated, and recorded, in circuit 7. If not so used, circuits 7 and onwards may be used for any desired purpose.

SUBJECT	CIRCUIT NO.	SET 1		SET 2		SET 3		SET 4	
I		FLIGHT 1		FLIGHT 5		FLIGHT 9		FLIGHT 13	
	2	FS	HD	C	HD	FS	HU	C	HU
	3		HU		HU		HD		HD
	4	C	HD	FS	HD	C	HU	FS	HU
	5		HU		HU		HD		HD
	6	FS	HD	C	HD	FS	HU	C	HU
II		FLIGHT 2		FLIGHT 6		FLIGHT 10		FLIGHT 14	
	2	FS	HU	C	HU	C	HD	FS	HD
	3		HD		HD		HU		HU
	4	C	HU	FS	HU	FS	HD	C	HD
	5		HD		HD		HU		HU
	6	FS	HU	C	HU	C	HD	FS	HD
III		FLIGHT 3		FLIGHT 7		FLIGHT 11		FLIGHT 15	
	2	C	HU	FS	HU	FS	HD	C	HD
	3		HD		HD		HU		HU
	4	FS	HU	C	HU	C	HD	FS	HD
	5		HD		HD		HU		HU
	6	C	HU	FS	HU	FS	HD	C	HD
IV		FLIGHT 4		FLIGHT 8		FLIGHT 12		FLIGHT 16	
	2	C	HD	FS	HD	C	HU	FS	HU
	3		HU		HU		HD		HD
	4	FS	HD	C	HD	FS	HU	C	HU
	5		HU		HU		HD		HD
	6	C	HD	FS	HD	C	HU	FS	HU

VISIBILITY. C = CLEAR, FS = FOG SCREENS   CONTROL. HU = HEAD-UP, HD = HEAD-DOWN

(ii) THE SUBJECTS. All the four subjects were qualified Test Pilots of the Blind Landing Experimental Unit at the Royal Aircraft Establishment, Bedford.

(iii) DATA REDUCTION. The six measures were integrated over ten second epochs from 2 minutes prior to touchdown through to touchdown. This data was then further grouped to 30 second periods giving four intervals before touchdown.

As the balanced design was not able to be completed the analysis that followed used data from only two circuits for each subject under each of the four conditions although all subjects completed at least ten circuits.

In summary therefore we have:-

6 physiological measures,
4 time epochs before touchdown,
2 viewing conditions,
2 display modes
2 circuits per working conditions per subject.

4. RESULTS

The data obtained was subjected to 6 analyses of variance, one for each physiological measure. The results of these analyses are summarised in Table 2.

TABLE 2. SUMMARY OF ANALYSIS OF VARIANCE RESULTS

Source of Variance	Physiological Measure					
	Arm Activity	Leg Activity	Skin Activity	Respiration Rate	Respiration Flow	Heart Rate
Periods (P)	**	-	-	-	**	***
Head-Up v. Head-Down (D)	-	-	-	-	-	*
Fog-Screen v. Clear (C)	*	-	-	-	*	***
P.D.	-	-	-	-	-	-
P.C.	-	-	-	-	-	-
D.C.	-	***	-	-	-	***

Key: * Statistically significant at p = 0.05
** " " " p = 0.01
*** " " " p = 0.001

In addition to these findings a significant difference in the level of response between subjects was demonstrated for the 6 measures. Whenever a significant difference shown in Table 2 was demonstrated it was always of the same general pattern, that is that higher physiological activity was associated with approaching the ground, and with the presence of fog-screens.

Table 3 illustrates the findings of what, from this study, appears to be the most sensitive measure, namely heart rate. The data shown is the average value across four subjects and two circuits per working condition.

TABLE 3. HEART BEATS (COUNT OVER 30 SEC.)

Time To Touchdown (mins)	FSHD	FSHU	CHD	CHU	Average
2	54.88	53.13	46.38	54.38	52.19
1½	57.00	56.38	47.13	55.25	53.94
1	63.00	58.75	51.13	58.25	57.78
½	68.75	61.50	56.88	61.88	62.25
Average	60.91	57.44	50.38	57.44	56.54

If the physiological data compiled as in Table 3 is ranked (1 = least activity) for each working condition with respect to the 4 time periods before touchdown then the sum of these ranks for each working condition demonstrates the increase in physiological activity during the course of the approach.

TABLE 4. SUM OF RANKS OF 6 PHYSIOLOGICAL MEASURES FOR 4 WORKING CONDITIONS OVER 4 TIME EPOCHS

Working Condition	Time to Touchdown (mins) 2.0	1.5	1.0	0.5
Fog-screen, Head down	10	11.5	18.5	20
Fog-screen, Head-up.	12	10	15	23
Clear, Head-down	9	12	15	24
Clear, Head-up	11.5	7.5	19	22

5. DISCUSSION

5.1. GENERAL. Experience in this trial indicates the feasibility of using physiological assessment techniques in the field without inconvenience to either the trial's staff or to the aircrew subjects. The fitting of the sensors was accomplished by non-specialist staff in less than 15 minutes before each flight and did not interfere with the pilot's airborne activities in any way.

With the exception of the carbon dioxide recording equipment all of the measurement techniques worked reliably over the period of the trials without causing any maintenance problems. Of the measures employed and within the limits of the data reduction and analysis techniques used it would appear that the most sensitive physiological parameter is heart rate, a finding that has been shown by many laboratory studies. It is known, however, that more sensitive analysis procedures are possible for the parameters recorded in this trial. For example, during the course of this trial one of the authors has developed a method of assessing changes in skin resistance which is more sensitive to the effects of working conditions than the methods used in this report (3). Similarly, Opton et al (4) have shown that the utility of heart rate measures can be improved.

5.2. ASSESSMENT OF TRIAL VARIABLES. In assessing the differences between working conditions that have been demonstrated in this trial two points should be considered. Firstly, not all of the planned flights were completed and hence the amount of data available is less than could have been desired. Secondly, all of the four subjects were experienced pilots familiar with the various aspects of the trial and less likely to show wide variations in response as the conditions were changed than would a group of less skilled pilots.

When differences were shown (see Table 2) the various physiological measures gave excellent agreement on the direction of the difference. Three parameters showed increased physiological activity as the time to touchdown decreased. Similarly, the same three measures showed heightened physiological activity when fog-screens were in use compared with no fog-screens. Only for heart rate was a difference between Head-Up and Head-Down display of information demonstrated and then at a low level of statistical significance. In these two latter cases the significance of the interaction should be borne in mind when making interpretations of the data.

6. CONCLUSIONS

1. Multivariable physiological assessment of pilot stress in the field is feasible both technically and administratively.

2. Data obtained from physiological assessments is capable of providing useful insights into the situation under study.

3. Further use of multivariable physiological assessments in both flight and simulated flight conditions as an assessment technique should be accompanied by the development of a more portable digital recording system, using the principles demonstrated so that a normative body of data can be assembled.

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FLIGHT DECK WORK LOAD AND
NIGHT VISUAL APPROACH PERFORMANCE

by

Conrad L.Kraft and Charles L.Elworth

Military Airplane Systems Division
The Boeing Company, Seattle, Washington, USA

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Conrad L. Kraft
Charles L. Elworth
Military Airplane Systems Division
The Boeing Company
Seattle, Washington

Abstract

Research with a night visual approach simulator has provided data supporting a logical explanation for about 16 percent of air transport accidents. The explanation is in the form of a two-part hypothesis: a descent path that nulls out some visual information and a delay in relative motion supplement of the same information. The missing topographic information allows incorrect interpretation of altitude and distance. Most operational examples of this class of accidents include information about crew distractions, critical intrusions and work loads. In recent investigations, the flight deck work loads were altered by varying the frequency of appearance of other traffic which the pilot was instructed to detect and report to ground control. Analysis of the effect of work load on performance revealed this to be a significant factor only as it interacted with terrain slope and pilot differences, but not otherwise. These investigations, along with previous ones in the series, have yielded quantitative data on a subtle aspect of night visual approaches that may lead experienced pilots into a dangerously low approach. While the study was conducted with commercial jet experience as a background, the problem is thought to extend to all types of operations and equipments - commercial, military, and private.

Objectives

During the first eight years of commercial jet operations, that is, prior to 1967, approximately 16 percent of the major aircraft accidents occurred during night approaches over unlighted terrain or water toward well-lighted cities and airports (1). Meteorological conditions in all cases were such that the flight crew could have employed visual reference to light patterns on the ground. In 1967, the accident rate under similar conditions rose to 17.5 percent (1). Accidents involving highly instrumented aircraft continue to occur during seemingly safe night visual approaches.

Accordingly, we set as our research objectives the following considerations:

- To determine the degree to which night visual approaches are unsafe.
- To determine how specific topography, light patterns, descent paths, etc. result in inadequate visual information.
- To determine how flight deck work load may influence approach performance under night visual conditions.

The results of the research will be used to identify requirements for hardware and operational procedures to make night approaches safer.

Operational and Methodological Problems

Our major emphasis is on the visual aspects of landing approaches, and research results have convinced us that at least some of the "pilot error" ascribed to approach accidents is based on incorrect assumptions concerning normal human visual abilities. For example, pilots seem generally unable to judge a safe approach altitude by vision alone if the terrain has an upward slope. They fly too low. On the other hand, they tend to follow too high an approach when only the airport is visible. Another finding is that they tend to use the pattern of city lights as a horizon reference even if it results in one wing being low.

Others have written of "illusions" and warned pilots of perceptions of height and distance which might lead pilots into dangerous operational conditions (2, 3, 4). Whatever the mechanism - illusions, subthreshold stimuli, or adequate but invalid stimuli - the fact remains that nonstructurally related accidents are occurring during night approaches under good weather conditions.

In our study of night visual approaches, we attack the problem in three ways. First, we study accident reports to search for clues relating the accident to the visual environment. Second, we analyze night approaches in terms of the visual information available to the pilot and what he would need to maintain or correct his flight path. Special emphasis is placed on those situations where information from vision outside the aircraft may tend to conflict with that provided by instruments. Third, we measure the actual path flown by experienced pilots in a simulator and compare this with requested path and with pilots' estimates of altitude.

It will surprise no one that a survey of accident reports involving commercial jets showed up many more differences than similarities in the visual environments where these accidents occurred. However, we were impressed with the difficulties faced by the pilot whose approach path provided him with a poor set of visual

cues - not the absolute minimum of dense fog, but rather conditions that would lead him to trust a VFR approach when visual information is marginal or possibly misleading. The most obvious of these conditions is the darkness of night when manmade sources of light provide the only visual stimuli.

The complex pattern of a city at night can replace to a large extent the normal daylight cues and the experienced pilot can successfully rely on them most of the time to get his bearings. There is a redundancy of such reference points in an approach over lighted terrain. However, an approach over water or unlighted terrain means that the visual reference points occur at a distance where altitude and sink rate would be more difficult to judge.

Our objectives were to measure the amount of information presented pilots by the external (to the cockpit) scene. This quantitative information was not available to those writing of "illusions" in prior articles. What was needed was to know the influence of this scene on pilots' estimates of their altitude and whether the estimates were compatible with the actual altitude that they would generate while letting down.

To obtain these measurements by asking pilots to fly night approaches to cities on various terrain was not compatible with the requirements for safety, economy, or adequate experimental control. The use of motion pictures to provide the night visual scene for use in simulators also proved noncompatible. The extremely small point sources of light on the ground from 20 miles away at altitudes of 20,000 ft. were too small and too dim to photograph on high-speed 35mm film. Slower film of higher resolution was not compatible with aircraft approach speeds and exposure times for night photography.

The photographing of models of cities for experimental purposes is limited by film grain and also by the insufficient resolution or speed of color film. Furthermore, photographing to provide specific viewing angles and uniform resolution is most difficult.

The adequacy of visual stimuli was not the only problem. Very senior pilots, first officers, private pilots, and nonpilots all have one thing in common - differences among individuals. We, therefore, had to turn to the methods of experimental psychology, with representative sampling, to gain adequacy of measurement.

Simulators that reproduce all the flight characteristics of a commercial jet aircraft are very expensive. Therefore, judicious selection of those aircraft characteristics most pertinent to the problem is required for the most efficient use of the conventional research budget.

Approach To The Problem

An approach to the problem was selected to provide (1) good quantitative data, (2) compatibility with the operational procedures and conditions, and (3) pertinent aircraft characteristics. The applicability of the final data was thus maximized as follows:

- Analytical investigation of cities, flight conditions, accident records, and airline procedures, in relation to visual abilities.
- Operational flights to obtain realistic data.
- Design and construction of a simulator containing the essential elements of visual operational conditions.
- Experimental investigation of pilot performance and judgments in aircraft approaches toward cities.
- Quantitative assessment of each of the factors and their interaction.
- Recommendations for improvements in hardware, procedures, and training through application of research data.

Development Of A Testable Hypothesis

Looking at the problem from the standpoint of the visual environment, we asked: "Was there something about those approaches in the accident reports that might have resulted in insufficient information or in false information to the pilot?" In this examination, we considered the visual angle that provides information to the pilot. This is the angle subtended at the eye by the nearest and farthest lights of the city as the pilot follows his flight path. To a pilot flying on a level course at a constant altitude, this angle increases progressively as he approaches the city. To a pilot descending vertically at a constant distance from the city, this angle progressively decreases. There is a specific flight path in which the visual angle subtended by the city remains constant. If the airplane is maintained on this path, the pilot may be losing important closure information without his awareness. This approach path follows the arc of a circle centered above the pattern of city lights, with its circumference contacting the terrain. Such a path provides no changing projection of the topographic plane formed by the pattern of city lights along the dimension that is, in visual terms, most relevant.

In addition to the changing projection of the topographic plane, visual information is available from the relative motion of the light pattern as seen from the cockpit. However, since this motion must exceed approximately one minute

of visual angle per second before it is perceived, approaches over dark areas do not provide relative motion cues until the aircraft is relatively close to the city. Figure 1 shows that at 240 mph and 3,000-foot altitude, motion would first be perceived eight and one-half to nine miles out. When slowing down and descending, as one would in an approach, the motion threshold occurs later. At 1,000 feet and a speed of 120 mph, the threshold distance would be three and one-half miles.

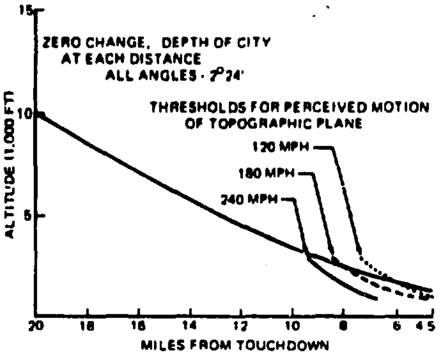

Figure 1. Zero change approach path and thresholds for perceived motion.

Figure 2 illustrates the ways in which visual angle of topographic plane projection and perceived motion relate to flight path and aircraft velocity for approaches to level and to graded terrain. The area of greatest interest is between 10 and 3.5 miles out, where dangerously low altitudes and fast sink rates may result from the interaction between inadequate visual information and topographical variation.

Simulation for Night Visual Approaches

A simulator for night visual approaches was constructed and the first studies were carried out with movie films taken of fluorescent chalk models illuminated with blue light. The cameras were equipped with proper filters and mounted on scaled approach tracks. With this simulation, the pilots provided altitude estimates but were not given control of their flight paths. In the current, more sophisticated simulation, the city model is situated atop an 8- by 10-ft. table, which would appear as a large light panel if the city were removed. The city light pattern is made of thousands of tiny raised translucent bumps in an otherwise opaque film. The city thus remains visible at simulated ground level, with each bump a point source of light. Selective coloring has been used to simulate lights of sodium yellow, mercury vapor, and tungsten. The city model in the simulator is scaled 6 inches to the mile. There is a tendency on the part of the pilots "flying" the simulator to try to identify the city from their past experience.

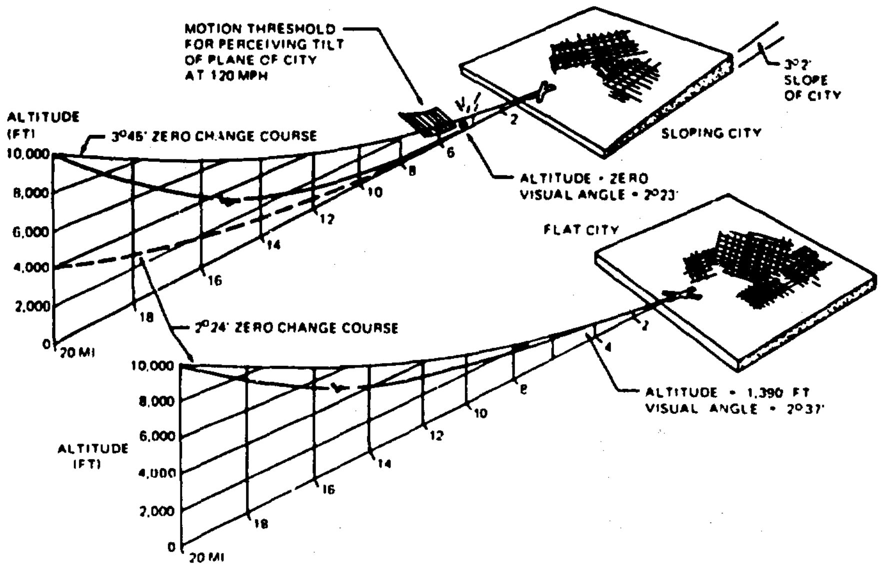

Figure 2. Influence of topography, distribution of lights, and motion thresholds on average approach paths

The table containing the city moves vertically and is mounted on a wheeled carriage that moves toward the pilot on rails. The pilot's control of the stick and throttle in the cab is fed through the motors that drive the table along these two axes. Distances from 34 to 4.5 miles from the airport can be simulated. Maximum altitude is 16,000 ft.; minimum altitude is minus 2,500 ft. The simulator is programmed to react like a 135,000-lb. commercial airliner in an approach. Maximum forward speed in level flight is 380 TAS; maximum climb rate is 6,000 fpm; descent, 8,000 fpm. Stall speed is set at 110 TAS, and the aircraft loses altitude at the rate of 12,000 fpm under stall conditions.

To make the simulation realistic, the pilot's view was restricted to one eye because at the distances simulated, there are no stereoscopic visual cues as there would be with the actual distances used in the simulator. The validity of the simulation is best represented in the enthusiastic acceptance by experienced pilots of how realistic an impression it creates.

Experimental Evidence

While the construction of the simulator's power, drive, and simplified computer was being completed, a static study of the influence of topography on night visual approaches was undertaken. This static study, done with still photographs of the model city, provided the information that the greatest overestimation of altitude would occur with a steady upward-sloping terrain; that a city with hills on the near or far side would lead to less overestimation than a uniformly sloping city would but to more overestimation than a flat city.

When the construction of the simulator was completed (Figures 3 and 4), it was possible to compare the results from the still photographs with pilot performance in the dynamic situation. Twelve Boeing instructors from Flight Crew Training each made 12 approaches, six to the city in a

Figure 3. Simulator with Pilot Seat Removed

Figure 4. Test Crew Flying the Boeing Simulator into "Nighterton"

flat position and six to the same model at a 3-degree slope. They were informed of the slope or lack of it before each approach. Two other variables were tested in the experiment: starting altitude (16,000 ft. and 10,000 ft.) and distribution of lights (airport only, airport with distant half of city, and airport with full city).

Pilots were instructed to choose their own approach path to the airport at the near edge of the display, except that they should attempt to be at 5,000 ft. 10 miles out and at 1,240 ft. 4.5 miles out, at which distance the problem ended. They were also asked to be flying 180 mph IAS at 10 miles out and 120 mph at 4.5 miles out. An x-y recorder at the experimenter's station makes a continuous record of the flight path generated by the pilot.

During each approach, the pilot received eight requests for altitude estimates, starting at the 18-mile point. He was forced to guess because there was no altimeter in the cockpit.

To increase the workload on the pilot during his approach, he was required to report the presence of other aircraft in the area. Two simulated aircraft orbited over the city, one clockwise, the other counterclockwise. A special switching arrangement made one or the other aircraft visible for 10 seconds at a time, for a total of eight such exposures during each approach. The pilot was alerted to the presence of other aircraft when he heard communications between the ground and the airplane he was to locate. On detecting the other airplane, he was to report its position and altitude relative to his own, and its heading.

Experimental Findings

Homogeneous Terrain

The performance variable of major interest was generated altitude (the approach actually simulated by the pilot). The table below shows the relative importance of the effects of the main experimental variables on generated altitude.

Source	Percent of Variance
Pilots	24.9
Distances	19.8
Slope of city	16
Light distribution	4.3
Beginning altitude	--

One of the main variables, beginning altitude, had no significant effect on generated altitude. The remainder of the observed variation in performance (the 35% that does not appear in the table) occurred as a result of two or more variables acting together. All such interactions included differences in distances or pilots.

The largest source of variation in generated altitude (25%) is due to differences among individual pilots. While individual differences are typically large in human factors studies, that finding is particularly interesting in this study because it is assumed that approach paths would be rather standardized for commercial jet aircraft. The performance of Boeing pilot instructors in our simulator suggests that there are broad limits in the range of altitudes chosen on the basis of visual reference.

The second largest source of variation in generated altitude is distance from touchdown (20%). This measure is actually a difference score, the difference between a straight path (between requested altitudes) and the path flown. The pilot started his run at an experimenter-controlled altitude (15,840 or 10,000 ft.) and was requested to be at 5,000 ft. 10 miles out and 1,240 ft. 4.5 miles out. Unexpectedly, this factor of distance from touchdown causes less variation in generated altitude than differences among pilots.

City slope, the main experimental variable, accounts for 16 percent of generated altitude variation and is the third most potent variable tested in this study. The effect of this variable was consistently that of causing the pilots to take a lower approach path, i.e., they flew lower when the city was sloping than when it was flat.

The remaining variable, distribution of lights on the terrain, had a small but significant effect on approach path (4.3%). It is the direction of this effect that is most interesting. We would expect that increasing the amount of visual information by adding lights would provide better reference information. However, our data suggest that more visual information may actually be detrimental if it tends to be misleading. Thus, the addition of lights in this study caused a greater deviation in approach path toward dangerous altitudes than was true when only the airport was visible.

It was anticipated that the detection of other aircraft would be easier when only the airport lights were on, and this expectation is supported by the data. Approximately four times as many aircraft went undetected when all or part of the city lights were on as when only the airport was lighted.

Returning to the major experimental variable of city slope and the performance variable of generated altitude, let's look at the two curves in Figure 5 for the effect of city topography on approaches to an airport when all the city lights are on. Although the pilots were informed prior to beginning each approach as to whether the city was flat or sloping, their flight paths were obviously quite lower when the city was sloping. The visual angle subtended at the pilot's eye by the city was very nearly the same at the 4.5-mile point for both cases - 2 degrees 49 minutes

for the flat city, 2 degrees 46 minutes for the sloping city. Beginning at the 8-mile point, the approach path to the sloping city is dangerously close to zero altitude.

What path did they think they were taking? Look at the shaded bars projecting upward from the points on the lower curve in Figure 5. The tops of the bars represent the pilots' estimates of altitude at these points. It appears that these experienced pilots thought they were at approximately the same altitudes as in the approach to the flat city.

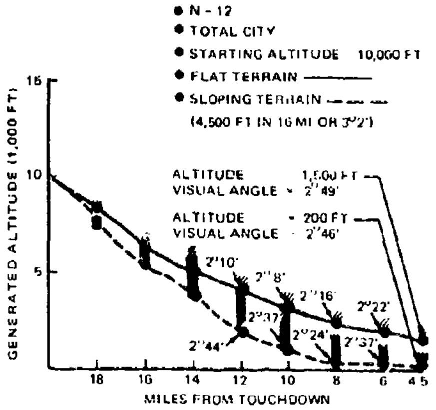

Figure 5. Influence of city topography on descent.

Heterogeneous Terrain

In the experiments discussed above, the runways, taxiways, and support areas had the same terrain as the city. Controlling airport terrain to conform with city topography allowed us to measure its effect as a separate independent variable. Although runway slopes exist that exceed 3 degrees, they are much more commonly graded to be approximately level and, therefore, do not conform to the surrounding topography.

The logical next step was to determine whether the influence of a sloping city was independent of the airport terrain.

In addition, there was the question of whether additional instrumentation - that of providing pilots with rates of climb and descent (without absolute altitude information) - would provide sufficient information for safe let-downs. It was an experimenter's "gamble" that these two variables could be studied in the same experiment using the prior experiment as a baseline.

The follow-on experimental design also included starting distance as a variable. Starting altitude had not proved to be a significant variable, but despite the close relationship of distance and altitude in any let-down, one could not assume a common influence.

The heterogeneous-terrain experiments indicated that very similar let-downs were accomplished by the pilots regardless of city topography for the 20 mile/10,000-ft. starting position only. This starting position is familiar to commercial pilots as this is the FAA regulated maximum altitude at 20 miles. It is assumed that approach/descent speeds could be set up successfully with the two available instruments from this familiar starting point with less dependence on the visual scene. However, when the starting point was the less familiar condition of 10,000-ft. altitude at 34 miles, the final altitudes were lower for the sloping city and the results conform to the visual angle hypothesis.

Figure 6 illustrates the similarity of the final visual angles and the lack of similarity in generated altitudes. The pilots' estimated altitudes are almost identical inside of the 12-mile distance, generally underestimating their altitude toward the flat city and overestimating their altitude on approaching the sloping city.

The authors would conclude that the city light pattern does have an influence on pilots' let-down performance independent of the plane of the runway.

Work Load

In this experiment, the flight deck work load of the operational situation was approximated by introducing a task of visually detecting and reporting the presence of other traffic. This task has provided data that concurred with some operational data; i.e., the difficulty of detecting other aircraft at night increases with the presence of city lights. The operational data obtained by others indicated that "flashing lights", high intensity areas, and lights of similar color were, in that order, detrimental to aircraft detection. These confusion stimuli exist in the "Nighterton" simulation, and our prior data concur in indicating that the presence of city lights decreases the detection of other aircraft by a ratio of about 4:1.

In all the studies, the reporting of other aircraft task had three parts: (1) the location in azimuth of the other aircraft's position relative to the simulator's flight path; (2) the detection and reporting of the other aircraft's relative heading; and (3) the detection and reporting of its relative altitude in respect to that of the simulator pilot's altitude. Location was reported in clock position; heading as "toward" or "away", to the right or left; and altitude as "above", "same", or "below". The criteria was $\pm 15^{\circ}$ for the first two areas of judgment and ± 1000 ft. as the equal category for

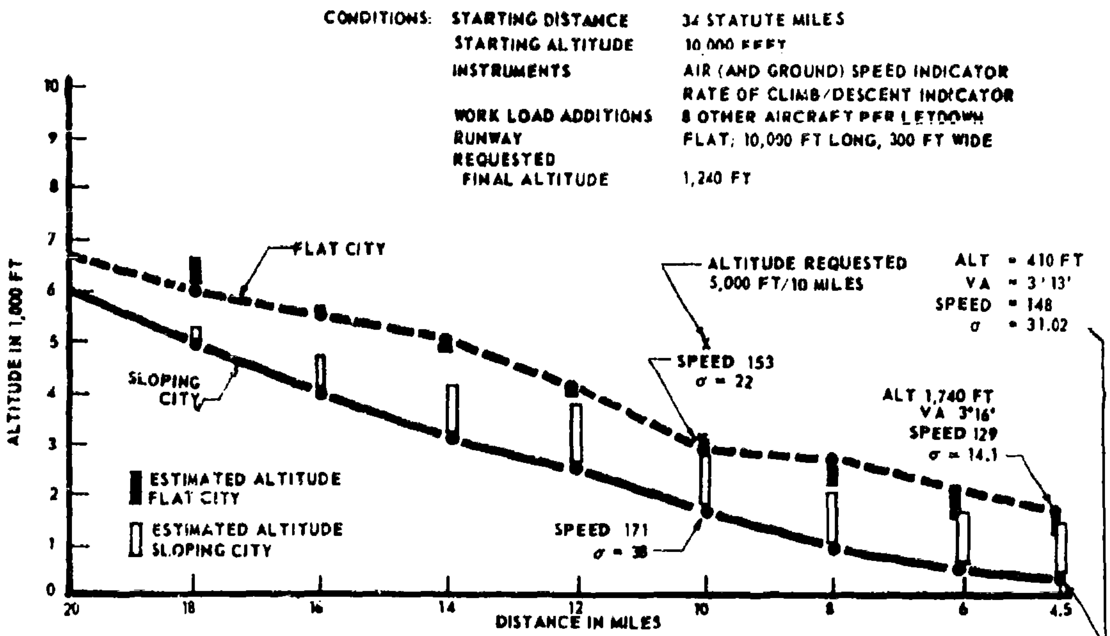

Figure 6. Average Letdown Performance to Flat and Sloping (3°) Cities. Generated Altitude.

altitude. To put the difficulty of this task in perspective, one needs to know that no aircraft remained visible longer than ten seconds.

The following table indicates that the proportion of correct responses is similar for each of the sub-tasks, city topography and starting distances. The average percentage is 35.6%, indicating the difficulty of this visual task.

Percentage of correct Reports of Other Aircraft During Night Approaches

		Location	Heading	Altitude
Flat City	20 mile	29	36	45
	34 mile*	37	42	45
Sloping City	20 mile	32	34	32
	34 mile*	30	35	24

*In this comparison, only those aircraft presented between the 20-mile and 4.5-mile points are considered, regardless of starting distances.

The Flight Deck Work Load Experiments

Work Loads

The investigations discussed thus far used a constant work load. The most recent investigations studied work load as a primary variable. The night visual approach simulator was modified to provide three aircraft flying over the city in separate orbits, their lights activated by stepping relays with nearly random sequencing. As many as 16 presentations of aircraft could be made between the 20-mile and 4.5-mile distances. The "light" work load was 3 to 4 aircraft; the "medium" was 8 or 9; and the "heavy" was 16 aircraft per let-down.

Topography/Aircraft Variable

The second major variable combined cities of three different topographies with three different airports. The flat city had the familiar (to our pilots) 10,000-ft. long, 300-ft. wide runway. This represented our control condition as these variables have been used on each of the earlier investigations. The second topographic condition was a 1.5° city slope and a 7,500-ft.

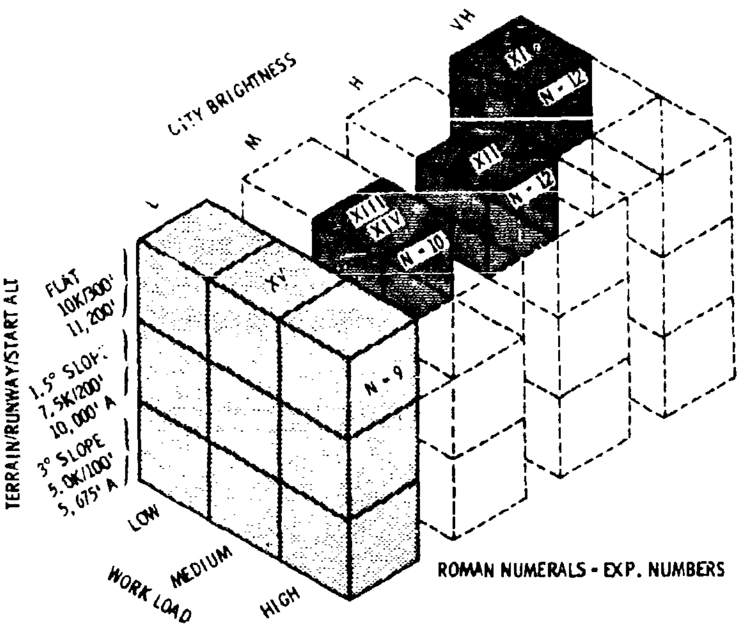

Figure 7. Work Load Experimental Design and Relationship with Other N.V.A.R. Experiments

long by 200-ft. wide runway.[8] The third topographic combination was a 3° slope and a 5000-ft. long by 100-ft. wide runway. The pattern of support buildings, taxiways, etc. were modified to provide very similar configurations with the requirement that they be operationally feasible. The runways were always flat and the strobe light path length was shortened to conform to decreased runway length.

Wind Shear

To minimize a possible tendency for pilots to depend upon fixed rates of descent for constant air speeds over approximately equal times, the simulator was modified to permit the introduction of wind shear conditions. Pre-programmed were 30 mph head and tail winds which would affect the aircraft between 3000 ft. and 6000 ft. of altitude. A third condition had zero wind shear in this altitude band. Above and below this band, there were no wind effects. Pilots were told of the existence of these wind conditions, but no wind information specific to a given trial was provided.

City Brightness

The illuminances of city lights are modulated by atmospheric moisture content, the proportion and particle size of air pollutants, as well as distance, altitude and other aircraft-related variables. The apparent brightness of the city will influence pilot estimates of distance and altitude. Included in these two investigations was the condition of low city brightness. Figure 7 permits the comparison of the several experiments with regard to the variables of city brightness, work load, and topography/runway dimensions.

Distribution of City Lights

The city lights represented a city 20 miles wide and the most distant light was 16 miles from the runway threshold (i.e., along the line of flight). One experiment was undertaken wherein "the city was built out to the airport"; i.e., the pattern of lights was contiguous from the airport perimeter lights. The second experiment was a replication of the first but with the city lights separated from those of the airport. This disjunctive pattern was produced by excluding from the model those lights around the airport and those extending beyond it for six miles.

Pilots

The Boeing Flight Crew Training organization was the source of our very experienced pilots. The men average some 17 years of flying experience, mostly in jets, including military, commercial and flight test. They form the cadre of instructors who train airline pilots in the operation of Boeing commercial jets, and as a group, they are familiar with most airports in the free world. There was one exception in our opulation. A North West Airlines Pilot, a First Officer, volunteered and did participate in the experiment with the disjunctive light pattern.

Pilot Briefing

The entire group of pilots had received a previous briefing on the results of our prior experiments, and they had access to all publications on this work. Most of the pilots had participated in one or more of our experiments and, therefore, they were versed in the known effects of terrain on night approaches.

The instructions for these experiments were written out and read by all participants before entering the cab. During the familiarization flight, they could ask questions of the experimenter who flew copilot during this first let-down. A summary was given verbally as a check-out. Before each of the nine experimental runs, all conditions of the city, runway, distance and altitude were reviewed over the intercom system. Only the conditions of wind shear and other-aircraft traffic load were not reviewed.

Let-down instructions were to make good a speed of 180 mph at 10 miles out and 120 at 4.5 miles out. Final altitude at 4.5 miles was to be 1,243 ft., the intersection of a 3° glide slope.

The Results: Flight Deck Work Load Studies

The starting altitude and distance were planned to provide a visual angle of 2°42', or 2.7°. This value is equivalent to the visual angle at 4.5 miles obtained when we previously studied the 16 mile deep, contiguous patterned city with an intermediate brightness. The flat city and the 3° sloping city match this angle at the start of each descent. The starting altitude for the 1.5° sloping city matches the FAA maximum at 20 miles and the visual angle is 3.06°.

As reflected in the major dependent variable of generated altitude, the net effect of starting with nearly common visual angles was to reduce the principal variables of "distance out" and "topography" to non-significance when all distances were included in the analysis. In all prior investigations for the "all distances" analysis, these variables were significant. The "distance out" variable was second only to individual differences among pilots in contributing to the overall variance.

The influence of topography on generated altitude remained significant for the 6 and 4.5 mile distances when these were analyzed separately. In its effect on estimated altitude, topography remained a significant variable in the analysis for the eight distances combined.

Performance variation attributable to pilots (individual differences) has always been highly significant, the probability of obtaining the observed variation by chance alone never exceeding the .001 level. The following table shows the probability levels for all analyses conducted on generated altitudes and estimated altitudes for each of the two experiments testing different work loads.

	EXPERIMENTS ON CONTIGUOUS AND DISJUNCTIVE LIGHT PATTERNS COMBINED				CONTIGUOUS LIGHT PATTERN EXPERMENT					DISJUNCTIVE LIGHT PATTERN EXPERIMENT			
	8-G	5-E	4.5G	4.5E	8-G	4.5G	6-G	S8-G	5-E	8-G	4.5-G	6-G	5-E
DISTRIBUTION OF LIGHTS (L)	NS	.05	.05	NS	—	—	—	—	—	—	—	—	—
CITY TOPOGRAPHY (T)	NS	.001	.001	.001	NS	.001	.01	NS	.005	NS	.001	.01	.001
WORK LOAD (WL)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
PILOTS (P)	.001	.001	.001	.001	.001	001	.001	.001	.001	.001	.001	.001	.001
DISTANCES OUT (D)	NS	NS	—	—	NS	—	—	—	NS	NS	NS	NS	NS
LXT	NS	NS	NS	NS	—	—	—	—	—	—	—	—	—
LXWL	NS	NS	NS	NS	—	—	—	—	—	—	—	—	—
TXWL	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	
LXD	NS	NS	—	—	—	—	—	—	—	—	—	—	—
TXD	.001	.001	—	—	.001	—	—	—	.001	.001	—	—	.01
WLXD	NS	NS	—	—	NS	—	—	—	NS	—	—	—	NS
TXP	.001	.001	.05	NS	.001	NS	NS	NS	.001	.02	NS	NS	.001
WLXP	.001	.001	NS	NS	.001	NS	NS	NS	.001	.001	NS	NS	.001
PXD	.001	.001	—	—	.001	—	—	—	.001	.001	—	—	.001
LXTXWL	NS	NS	NS	NS	—	—	—	—	—	—	—	—	—
LXTXD	NS	NS	—	—	—	—	—	—	—	—	—	—	—
LXWLXD	NS	NS	—	—	—	—	—	—	—	—	—	—	—
TXWLXD	NS	.001	—	—	NS	—	—	—	.02	NS	—	—	NS
TXWLXP	.001	.001	E	E	.001	E	E	E	.001	.001	E	E	.001
TXDXP	NS	.001	—	—	NS	—	—	—	NS	.001	—	—	.02
WLXDXP	NS	NS	—	—	NS	—	—	—	NS	NS	—	—	NS
LXTXWLXD	NS	.02	—	—	—	—	—	—	—	—	—	—	.001
TXWLXDXP	E	E	—	—	E	—	—	—	E	E	—	—	E

* 8 - NO OF DISTANCES ANALYZED OR 4.5 - THE SINGLE DISTANCE ANALYZED — - DOES NOT APPLY
G OR E - GENERATED OR ESTIMATED ALTITUDE NS - NONSIGNIFICANT E - ERROR TERM

Figure 8 illustrates that, for the 8.0, 6.0, and 4.5 mile distances in the let-downs, the effect of topography of the city and runway configuration was to result in lower flight paths. This statement is true only for the contiguous light pattern which was modeled after those cities which have built out to surround their coastal airport. The figure illustrates that the pilots' estimates of their altitude were similar to the generated altitude for the intermediate condition, that of the 1.5° sloping city and 7,500-ft. long runway. Their estimates of altitude approximated the overall mean, underestimating the flat topography and overestimating their altitude above the 3° sloping terrain.

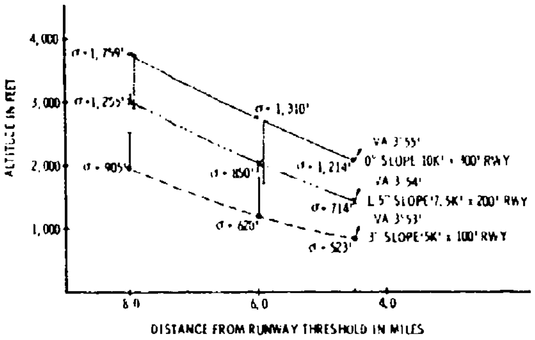

Figure 8. Generated and Estimated Altitudes for Approaches to Contiguous City Flight Pattern as a Function of Topography and Runways

The experiment with the city whose light pattern was contiguous to the airport adds further support to the visual angle hypothesis. The let-downs whose final 3.5 miles (i.e., from 8.0 to 4.5 miles) are depicted in Figure 8 terminate at altitudes that represent visual angles of 3°54' ± 1 minute.

These visual angles are from 50' to a degree larger than we would have expected from the starting visual angles and prior experimentation. In previous studies with the same city and the same runway (10,000 ft.), but with intermediate brightness, the average visual angle was 3°04', whether the runway had the same slope as the city or remained flat. It could be argued that this visual angle difference is due to the brightness difference and that runway length/width configurations are of little import. At this time such a statement remains merely an hypothesis; an alternative hypothesis is suggested by the increased variance found for the flat city and its familiar (to these pilots) 10,000-ft. long by 300-ft. wide runway. That is pilots may have remained higher as a cautious response to the less familiar runways, this higher altitude corresponding to a larger visual angle. Support for this viewpoint may be found in the following table, which shows that for the matched work load conditions, the standard deviations for the low brightness flat city are nearly three times as large as those for the intermediate brightness city. This comparison is across experiments although the separate samplings of the pilots are from the same population and all had prior briefing on the effect of slope. The very large variance may, therefore, be a result of their being extra careful against sloping terrain and co-varying runway lengths and/or relaxing when faced with the "familiar" and "safer" conditions.

Variability in Approach Altitudes at Three Distances from Cities of Two Brightnesses and with Medium Flight Deck Work Loads

Brightness	Topography	Runway	8 Miles
Intermediate	Flat	10K	σ = 739'
Low	Flat	10K	2301
Intermediate	3° Slope	10K	872
Low	3° Slope	5K	940
			6 Miles
Intermediate	Flat	10K	593
Low	Flat	10K	1661
Intermediate	3° Slope	10K	721
Low	3° Slope	5K	702
			4.5 Miles
Intermediate	Flat	10K	512
Low	Flat	10K	1544
Intermediate	3° Slope	10K	619
Low	3° Slope	5K	510

As mentioned previously, pilots show a general underestimation of altitude above the flat city, good approximation of true altitude with the 1.5° sloping city, and overestimation on approaching the 3° sloping city. Figure 9 illustrates how these estimates varied with the flight deck work load. Had this experiment dealt only with the two extremes of the "topography/runway" dimension, a systematic inverse relationship might have been postulated. The inclusion of the 1.5° slope/7.5K runway level reflects no linear effect of work load. The replication of this experiment, with the disjunctive city light pattern, shows underestimations for all topography/runway combinations. Also the underestimations are very slightly greater for each work load which is consistent only with the above data for the flat city.

These results imply that, if estimated altitude varies with this kind of flight deck work load, it will probably be measured only in an experiment where the analysis can include (or hold constant) the simulated aircraft's actual altitude.

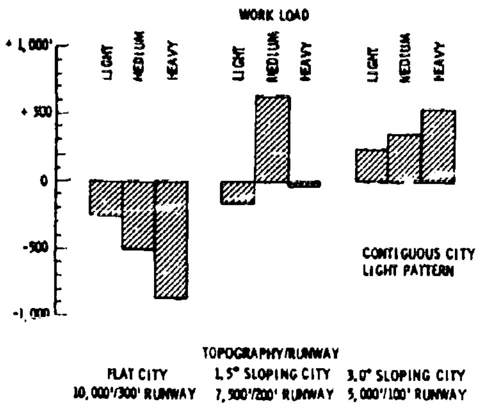

Figure 9. Altitude Estimation Error as a Function of Work Load and Topography/Runway Configuration

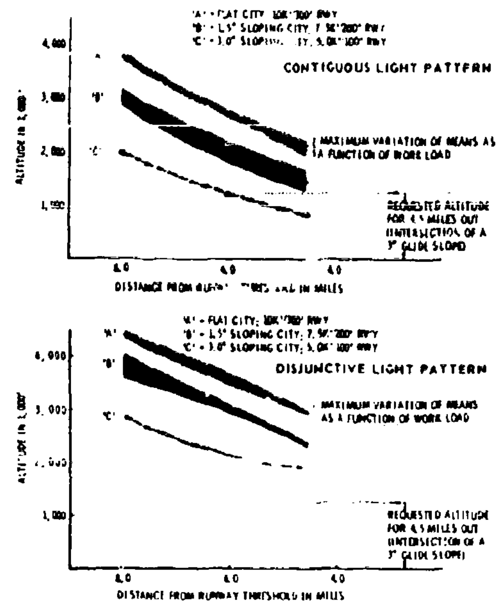

Figure 10. Let-down Performance with Different Work Loads and Different City Light Patterns

Earlier data with the intermediate city brightness had indicated that the disjunctive city light pattern was the more difficult city against which to make night visual approaches without altimetry references. This effect, though consistent, was small as the mean final altitude varied between 135 and 170 feet between the contiguous and disjunctive light patterns. There was a larger difference found when pilots descended toward airports not surrounded by city lights. The following table shows the magnitude of this effect:

City Topography	City Light Pattern: Disjunctive	City Light Pattern: Contiguous
Flat	612'	442'
3° Sloping	570'	435'

This tendency to fly higher toward the smaller visual scene may be a cautious behavioral pattern associated with the smaller image and slower rates of change.

In the work load experiments, the city brightness was the lowest available with the simulator and represented those atmospheric conditions which would attenuate the brightness of point-light-sources without imposing increased luminous areas due to diffusion. The influence of city light intensity interacting with that of the pattern of lights appears to be inconsistent with the prior data. Pilots fly higher approaches to the disjunctive light pattern in the work load experiments rather than lower. Figure 10 illustrates that this difference is 765, 948, and 1014 feet for the topographic/runway conditions identified as "A", "B", and "C". However, if we postulate that pilots respond to the disjunctive city of low brightness as though they were flying toward the airport lights alone, then the current and former data are consistent. This is most apparent when brightness conditions are compared for the flat city/10,000-ft. runway. The intermediate brightness produces about 600 feet of difference and low brightness 765 feet of difference in mean altitude. The larger differences between the two light patterns, in terms of generated altitude performance, are associated with the pilots' flying to shorter runways. Possibly pilots respond to the area of the light pattern rather than to its cognitive content. Figure 11 illustrates that the overall visual angle increases with the flights toward the shorter runways and the cities of greater slope. The pilots did not fly to make the visual angle of the runway a constant. Had they done this, the final altitude for conditions with the shorter runways would have been higher than that with the longest runway.

Work load as a variable shifts the mean altitude within the ranges shown in Figure 10. The "zip-toned" area on either side of the means illustrates the maximum variation found among the means. The reader should be cautioned not to interpret this shaded area as the standard deviation or that the upper limits are always associated with a light work load. The means do not show such systematicness. What is illustrated is that, within the work loads studied, the mean performance was modulated in three different patterns as a function of distance out. These patterns of variation either increase, remain similar, or decrease with decreasing distances from the runway. These patterns and the ANOVA reflect that the main effect and the first order interactions within any one distance are not significant.

In these experiments, flight deck work load is both an independent and dependent variable. We have, up to this point, discussed its

Runway	Topography	Contiguous City Light Pattern — Work Load: Low	Medium	High	Disjunctive City Light Pattern — Work Load: Low	Medium	High
10,000/300'	Flat	2,210' 4.14°	1,937' 3.64°	2,137' 4.01°	2,854' 5.34°	2,837' 5.31°	2,882' 5.39°
7,500/200'	1.5°	1,617' 4.31°	1,415' 3.83°	1,281' 3.58°	2,332' 5.54°	2,332' 5.54°	2,248' 5.39°
5,000/100'	3°	849' 3.94°	859' 3.90°	760' 3.77°	1,766' 5.66°	1,937' 5.98°	1,810' 5.74°

Figure 11. Altitude and Visual Angles at the 4.5 Mile Distance

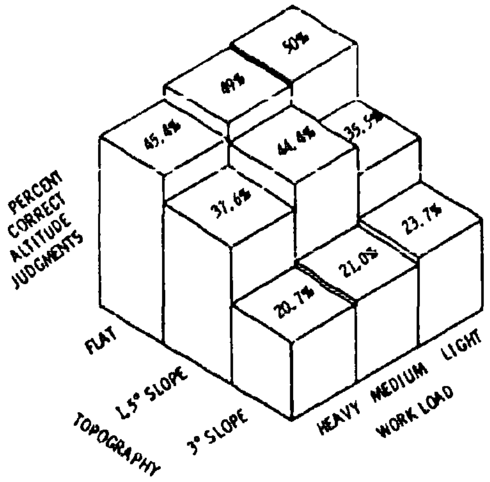

Figure 12. The Influence of City Topography and Crew Work Load on Judging the Altitude of Other Air Traffic

influence on flight performance, or as a dependent measure. We recorded pilot performance in detecting and reporting the position, heading, and altitude of other aircraft. These performance measures pertain to how well the pilot performed on the independent variable, work load. These data tell us that the pilots time-shared their tasks in about the same proportion for each work load.

The proportion of correct responses in detecting and reporting the azimuth position, the heading, and the altitudes approximated 35 percent. This is the approximate proportion found in prior experiments with the intermediate work load condition. The proportion of correct judgments was common for each work load. This is reflected by the percent of correct altitude judgments shown in Figure 12. The influence of "work load categories" is not systematic and of limited size compared to the large effect of topography. The greater the slope, the lower the proportion of correct altitude judgments. These data, pertaining to the contiguous pattern of lights, may reflect that this lower performance may be associated with the greater probability that the other aircraft lights must be detected against the city lights. A similar result may be expected if the altitude of other aircraft are more difficult to judge when the perceived horizon is higher than the "true" horizon. Further analysis may support one or the other of these explanations, but at this point in time, either hypothesis is acceptable.

The complex interactions of work load x topography/runway x pilots has proved difficult to organize or illustrate. Bivariate analysis depicted in three dimensions show some aspects of this complex function, but at this level of analysis, they tend to complicate rather than clarify. A portion of the problem may be illustrated in the frequency diagrams of Figure 13. The work load distributions include all topographies and runway conditions. These work load distributions are similar in their shape, the central tendency, and the standard deviation. The numbers within the area of the distributions represent the pilots designated by number. Each pilot's number should appear three times in each distribution. Their position along the horizontal axis connotes the pilot's contribution to the mean in any one let-down. These data pertain to the final altitude and these are difference-scores above or below the requested 1,243 feet.

It will be noticed that Pilot #1 flew higher and much more variantly under the light and medium work load than under the heavy work load. Pilot #7 flew higher under increasing work load but maintained similar variances for the "light" and "heavy" conditions. Pilot #6 flew lower and his variance increased with each increased work load.

These examples illustrate the pilot x work load interaction. The interaction of pilot x topography/runway is illustrated by Pilot #5 who flew lower with the increasing slope and shorter runways. Pilot #5 also illustrates the second order effects in that heavy work load increases his variance but not his flying lower, the latter being the influence of the topography/runway variable.

Conclusions

We conclude that flight deck work load in the form of other traffic to detect and report is a significant variable in affecting altitude and estimated altitudes during let-downs. The effect is a complex interaction among this

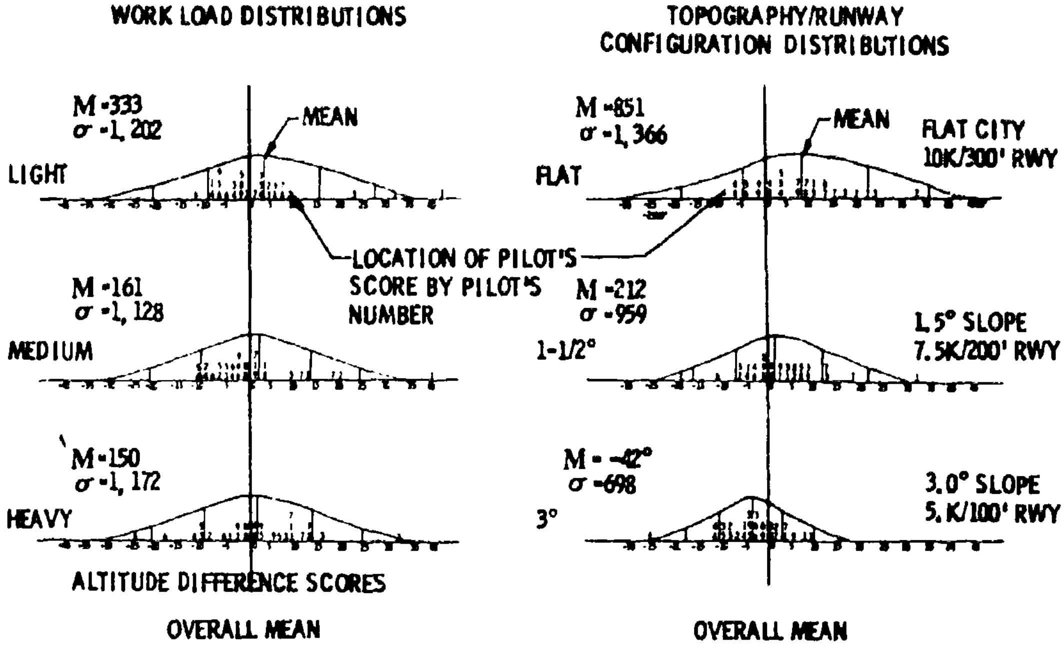

Figure 13. Distributions of Generated Altitudes by Work Loads and Topography/Runway. Position of Scores Are by Pilots' Numbers.

work load, pilots, and the city topography/runway conditions. Within the levels of work load studied here, some pilots may improve their performance under heavier work loads, some may be unaffected, and some will deteriorate in their performance.

We also conclude that pilots acquire through their training and experience a visual frame of reference that approximates a safe and conventional flight path onto a flat terrain. Many successful approaches are made with this reference, particularly with assistance from instrumentation. The night visual approach accidents with highly instrumented aircraft then may occur when the light pattern, topography, etc. provide invalid visual information, and circumstances are such that other sources of information are not referred to or fail to provide corrective information. Illuminated topography at night may also influence experienced pilots in their estimates of the altitudes of other aircraft in the terminal area.

Recommendations

In future investigations of work load, it is recommended that the plan be constrained to (1) include sufficient experimental degrees of freedom that complex effects may appear; (2) that work load be treated as both an independent and dependent variable; and (3) operational paradigms be considered for the work load, the overall task, and the simulation model.

In addition to these recommendations for all aviation safety, we consider that the modification of valid visual angle information occurs as a function of natural, economic, and chance conditions; that is, topography, distribution of population, irregularity of lights within city limits, attenuation of brightness and clearness of lights by atmosphere. Man has also by design made certain cities or airfields more dangerous than others. He was designing, in these instances, for man's other comforts or

safety when he created the more dangerous airports for night visual approaches. He locates airports away from cities, requiring approaches over water or over deserted farm lands, to avoid noise and potential injury for the terrestrial population. He builds airports by filling in shorelines and by using remote land. In solving some safety problems, he may unexpectedly raise others. Operations research people will undoubtedly see the need for their type of work in this overall problem.

The following city/airport/approach features are considered to aggravate this problem:

- o An approach over dark land or dark water where lights to the side and below the aircraft do not exist.
- o A long straight-in approach to the airport located on the near side of the city.
- o An airport runway length-width relationship that is unfamiliar to the pilot.
- o The airport situated at a slightly lower elevation and on a different slope from the surrounding terrain.
- o The navigational facility located some distance from the airport.
- o Substandard lighting of the runway, and other landing aids not available.
- o A sprawling city with an irregular matrix of lights spread over various hillsides in back of the airport.
- o Industrial smoke or other obscurations which decrease the brightness of lights as they interact with the distribution of lights about the airport. Cities on irregular terrain with remote airport may be less safe on clear nights.

The data being developed at Boeing support the visual angle hypothesis as one systematic explanation of night visual approach accidents. Investigations of possible solutions to this problem and their interaction with other phases of operations will take time. However, there are immediately available means for potential reduction of night visual approach accidents. These include more frequent reference to altimetry - barometric or radar, cross checks with other crew members, and most important of all, knowledge and awareness of the special problems associated with these approaches.

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EXPLORATORY STUDY

OF

PILOT PERFORMANCE DURING

HIGH AMBIENT TEMPERATURES/HUMIDITY

by

Stephen Moreland
John A. Barnes

Aviation Branch
Systems Research Laboratory
U.S. Army Human Engineering Laboratories
Aberdeen Proving Ground, Maryland

SUMMARY

HISTORICALLY, THE DESIGN and development of aircraft environmental systems have been largely inadequate because of the lack of suitable quantifiable data describing human performance changes under high cabin temperatures. It was the purpose of this study to explore techniques which could provide this quantifiable information and to assess actual pilot performance in a hot environment.

A prototype OH-6A helicopter was instrumented as the test vehicle. Four experienced pilots flew precision air patterns, observed and recorded ground targets, and performed normal flight duties of monitoring flight and engine instruments and other tasks during two-hour flight test periods. Four separate clothing configurations were worn by the pilots during the study.

During each flight two observers simultaneously measured pilot physiological and psychological performance as well as the crew station environment. The physiological performance was measured by heart rate, skin and rectal temperatures, and perspiration weight loss. Measures of psychological performance were defined as photopanel exposures of the instrument panel during precision flight patterns, response and reaction time measures, ground target identification, and assessments of subjective comments during post-flight debriefings. Both airborne and ground environmental measures of Dry Bulb, Wet Bulb and Globe Temperature were taken to determine the Wet Bulb Globe Temperature (WBGT) Index of heat stress, which provided a base by which pilot performance changes were compared.

Stepwise multiple-regression program, Pearson correlation, analysis of variance and t tests of significance were employed on the data to describe the relationships of temperature changes with pilot performance factors. The following statements generally summarize the results of the study:

1. Pilot performance (P_1) decreased and performance variability (SD) increased above a WBGT Index of 85°F.

2. The predictor performance equations determined by the multiple-regression program indicated that skin and rectal temperatures were highly related to pilot performance.

3. Pilots' reaction times increased as either ambient temperatures or rectal temperatures increased.

4. Pilots performed (P_1) better when they encountered light to moderate aircraft turbulence than they did on non-turbulent flights.

5. Pilot subjective judgments of cabin heat were highly inconsistent with environmental measurements.

6. Weight loss from perspiration appeared to have a positive correlation with performance (P_1).

7. The clothing and equipment configurations worn by the pilots (including body armor) had no significant effect on their performance (P_1).

8. The cabin heat did not significantly affect the pilots' ability to observe ground targets.

9. Large differences in performance (P_1) variability among pilots were due to basic pilot techniques (regardless of experience).

10. No constant relationship could be determined between ground and airborne measures of WBGT.

Limited aircraft and pilot availability allowed only four subjects to be used during the study, of which two completed all required flights. The above results, therefore, should be considered only as trends for the subjects and conditions tested.

The techniques used during this study did successfully measure both a large portion of total pilot performance and the cockpit environment. The multiple-regression program enabled comparisons of pilot performance and environmental sub-factors on large volumes of data, which heretofore would have been impossible. Though environmental variables could not be controlled, they could be accounted for, measured and correlated with other variables using the multiple-regression program. It may be hypothesized that if these variables can be accounted for and correlated, then the basic approach of inflight measurement of human performance certainly offers the potential of obtaining realistic assessments of new crew station designs and may ultimately be the best approach to developing the type of quantified information needed to develop crew station design criteria and standards.

In conclusion, this study provides a good baseline from which to structure future inflight research. Certainly, the techniques employed as well as the results should be further verified.

OBJECTIVE. This study was undertaken with the following objectives:

1. To determine if changes in pilot physiological and psychological performance could be detected and correlated with changes in relatively high crew station ambient temperature, humidity, and solar radiation.

2. To assess quantitatively, the compatibility of pilots wearing complete combat flight clothing and survival equipment, with a new (prototype) Army aircraft system operating in a hot, humid environment. The intent of this analysis was to point out hardware and clothing problem areas, if existing, and make appropriate corrective design recommendations before the aircraft became operational.

PROBLEM BACKGROUND. Isolating and measuring the factors contributing to pilot fatigue and efficiency has challenged the scientific community since aircraft began to fly. The principal question unanswered has been to what degree do these factors contribute to or cause human performance decrements and errors, and ultimately, to what degree should they be considered in the design of the aircraft.

Previous Army field reports have suggested that one of the most significant environmental factors contributing to pilot flight performance decrements may be the combined effect of high temperature and humidity. A search of related literature*, however, indicates that no one has been able to define these decrements in sufficiently precise quantifiable terms to verify significant performance changes or fatigue, or to establish adequate criteria for the design of aircrew environmental control/ventilation systems (ECS) and related aircrew clothing and survival equipment.

The design and development of ECS hardware has by necessity been determined more by crewmembers' subjective opinions and, to some degree, by what the airframe contractors happened to furnish as "off-the-shelf" hardware and systems. Unfortunately, subjective opinions are difficult to design to, are unreliable regarding estimates of heat, and in general do not provide the framework of data needed to develop crew station design standards.

There is a tendency to rely on an assumed ability of the aircrew to adapt to the environment. This allows the tradeoff arguments of increased costs and weight to dominate the design of the crew station, to the neglect of an adequate environmental system.

The net effect of this design approach has been that Army crews, in order to compensate for inadequate cooling/ventilation, make field changes such as removing the doors from the aircraft to provide additional ventilation.

The increased performance capability of current and projected Army aircraft (LOH, AH-56A, AH-1G, UTTAS, etc.) however, will require that the doors and/or windows remain in place to achieve the full aircraft flight performance envelope. Their mission requirements will require flight at near ground levels at which reflected solar radiation and high air temperature levels will, in warm climates, likely aggravate the crew heat stress problem.

METHOD

AIRCRAFT AND STUDY SITE. A prototype light observation helicopter (LOH, OH-6A no. 4211, Figure 1) was instrumented as the test vehicle as illustrated in Figures 2 and 3.

Fort Rucker, Alabama, was selected as the study site because of its capability to maintain and support the aircraft, availability of additional personnel needed to conduct the study, and a favorable climatological history, which indicated that relatively high temperatures and humidities would prevail during the study period. Predictions were: August 1966, 91°F mean maximum temperature with 70% mean Relative Humidity (RH); September 1966, 88°F mean maximum temperature with 65% RH.

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* See AFSCM 80-3 (12), Hendler (4), Jones (6), and Joy (7)

Figure 1. Above: Takeoff of prototype OH-6A light observation helicopter (LOH) during environmental study at Fort Rucker, Ala., August 1966.

Below: Aerial view of ground target & crew. The view shown is one of twenty target configurations displayed to the pilots during each flight as an observation & reporting task.

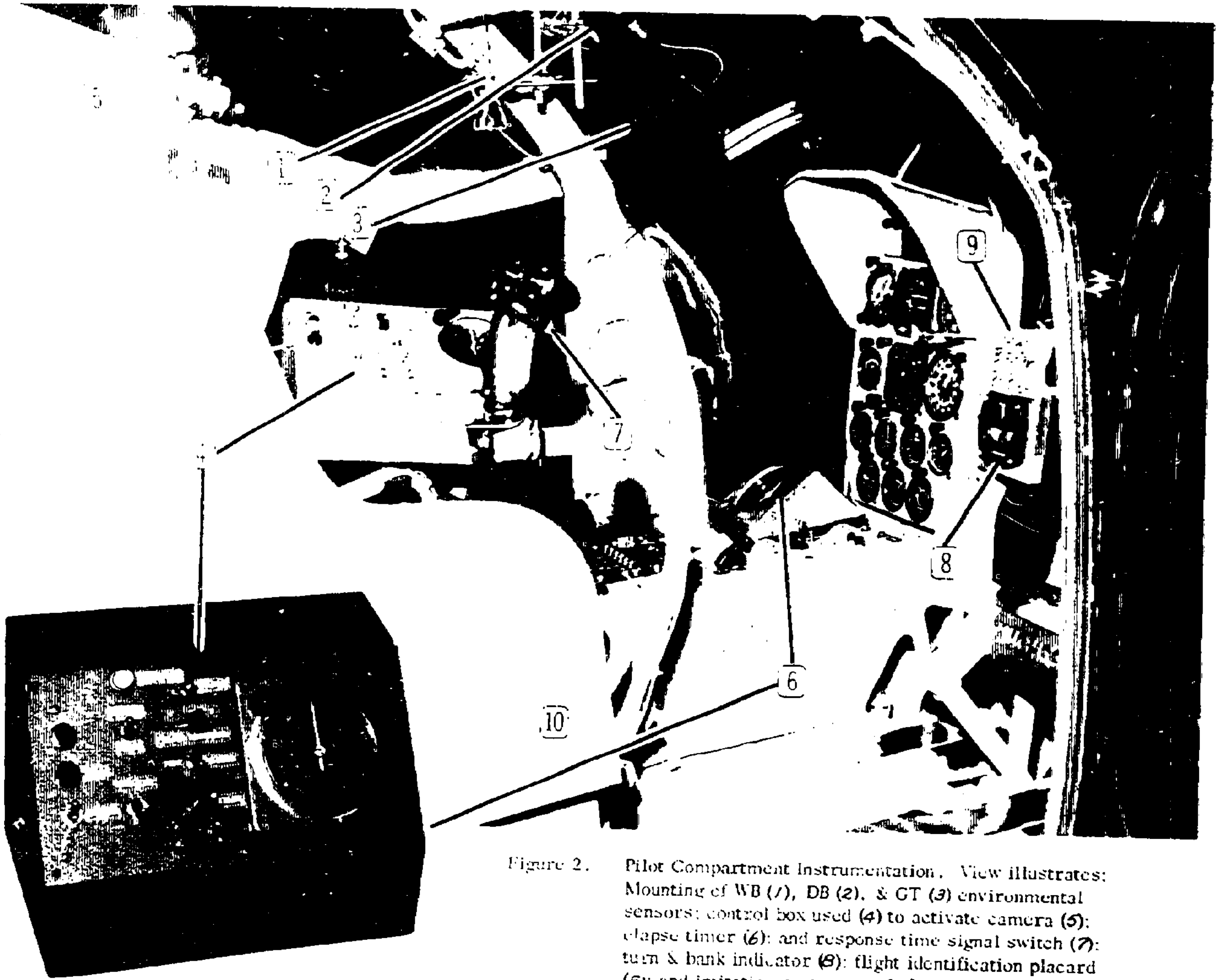

Figure 2. Pilot Compartment Instrumentation. View illustrates: Mounting of WB (1), DB (2), & GT (3) environmental sensors; control box used (4) to activate camera (5); elapse timer (6); and response time signal switch (7); turn & bank indicator (8); flight identification placard (9); and imitation seat armor (10).

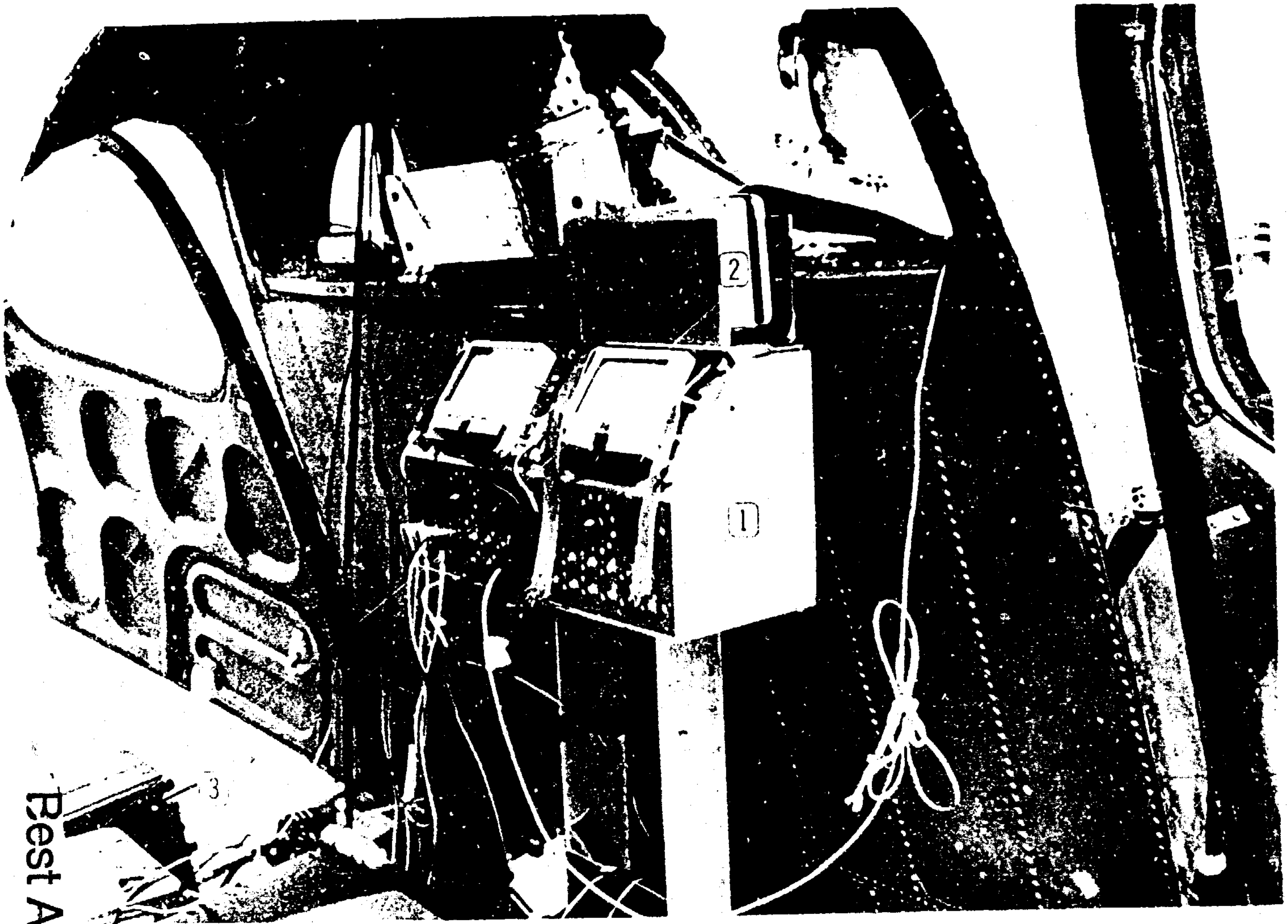

Figure 3. View of instrumentation installed for the physiological observer within the passenger compartment. Shown are: (1) Tele-thermometer displays, (2) electrocardiograph recorder; (3) oscilloscope, and associated wiring to physiological and environmental sensors.

SUBJECTS. Four fully qualified Army LOH pilots served as subjects. Medical and personal history data, flight experience, and anthropometric measurements of each subject were reviewed to determine the selection and matching between subjects. The pilot-subjects had similar flight expermence, were highly qualified, highly motivated instructor pilots, and as permanent residents of the Fort Rucker area, were acclimatized* and accustomed to flying in that area. Their qualifications tended to assure that learning effects, performance and flight variability due to acclimatization or area peculiarities like air traffic, weather conditions, special regulations, etc., would be minimized. No attempt was made to control or change the living patterns of the pilots during the course of the study. All were family men and enjoyed normal work and home activities. They were asked to be rested and not to fly other aircraft the day they were to fly as subjects.

PILOT-SUBJECT FLIGHT SCHEDULE AND CLOTHING MATRIX. The pilot flight clothing and survival configurations A, B and C, illustrated in Figure 4, were considered representative of what Army aviators are currently wearing and will be wearing in the near future. They were worn by the subjects during the study to duplicate the thermal insulation effects of operational clothing and equipment. The ventilated clothing configuration D (Figure 4) was added to the study for an assessment, rather than as part of the experimental design.

The experimental design for the study required each subject to serve as his own control. A total of 11 flights per pilot was scheduled, two in the morning plus nine in the afternoon. Eleven flights appeared to be adequate to sample the temperature region of concern (WBGT range of 80°F through 100°F). The subjects, flights and clothing configurations were assigned according to a random-number matrix to minimize experimental bias factors.

AM flights were scheduled for one hour and PM flights for two hours. The AM flights were to be completed during the hours of 0530-0900, to obtain a level of pilot performance during cool or more ideal temperature conditions (WBGT $<$ 85°F, but preferably within a range 70-80°F). Theoretically, it would have been desirable to duplicate two-hour AM flights for each two-hour PM flight flown, but this approach had to be abandoned because it was impossible to guarantee sufficient pilot and aircraft availability or to control ambient environmental temperatures. On the other hand, there appeared to be considerable evidence, both in the literature and from trial flights before the start of the study, to substantiate that no more than one-hour AM flights were needed.

1. Previous studies by Hornick (5), U. S. Army (13), and others indicate that measures of pilot flight performance (aircraft heading, altitude and airspeed control, navigation, etc.) indicated that there were no effective performance decrements or indications of fatigue during flights up to four hours duration, in a low altitude high speed flight simulator (operating with an assumed constant cool room temperature). These simulator flights also exposed the pilots to random gusts and vibrations up to .4RMS G and 1-12 CPS.

2. Trial flights of 1-2 hours in the prototype OH-6A before the start of the study indicated that pilot performance (P_I) seemed to level off within one hour.

3. The pilots' physiological responses were not expected to change significantly from the normal classical form during cool flights; i.e., some deviations at the beginning of the flight, then gradually returning to a normal state.

Two-hour PM flights were selected to enable ample time for physiological changes to occur, as has been demonstrated by studies of Hendler (4), DuBois (2) and others. These flights were to be completed during the hours of 1000-1600, to utilize the period of highest temperatures (WBGT $>$ 85°F) in the Fort Rucker area.

PILOT PERFORMANCE AND PHYSIOLOGICAL OBSERVERS. During each flight two observers (usually non-pilots) obtained simultaneous pilot physiological and psychological performance and crew station environmental measures. They also assisted in the instrumenting and weighing of the pilots on the ground, and conducted post-flight pilot debriefings.

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* Previous work by Hendler (4) suggests that performance measures taken on acclimatized personnel would not be as sensitive to daily fluctuations of temperature and humidity as non-acclimatized personnel.

A. Army fatigues, armor chest plate.

B. Nomex fire resistant coveralls, armor chest plate.

C. Nomex fire resistant coveralls

D. Ventilated flying suit.

Figure 4. Clothing Configurations

The observers were also required to closely monitor the pilot's physiological condition inflight; primarily because no safety pilots were used during the flights and the fact that inflight heat stress exposure could not be accurately predicted. The following predetermined pilot physiological safety limit criteria were used if a judgment to cancel the flight was necessary:

1. Any heart rate above 140.

2. If heart rate at takeoff was less than 100, the flight was to be terminated if the heart rate increased to 120.

3. Any rectal temperature exceeding 100.5°F.

4. If starting rectal temperature was less than 99.5°F, the flight was to be terminated if the temperature exceeded 100.0°F.

5. In all cases the flight was to be terminated if the rectal temperature exceeded 100.5°F.

A flight surgeon was also available for consultation via radio link, if required. Frequently, a flight surgeon flew on the flights as the physiological observer.

GROUND CREW. A ground crew was also required for each flight to periodically change the configuration of the ground target, measure ground level meteorological conditions, and occasionally monitor the pilot physiological data which was either communicated or telemetered to the ground station. They also prepared the next pilot-subject ahead of schedule to minimize flight turn-around time.

PSYCHOLOGICAL PERFORMANCE MEASUREMENT AND EQUIPMENT.

<u>Precision Flight Pattern</u>. A precision flight pattern entitled BRAVO (Figure 5) was flown to obtain measures of pilot psychomotor flight tasks. No safety pilot was carried in the aircraft; therefore, the pilot had to fly the pattern as well as perform the pilot's normal duties of monitoring flight and engine instruments, fuel management, communications and other tasks. These normal duties appeared to be similar to the concentration, decision making and aircraft control activities anticipated for pilots flying LOH missions.

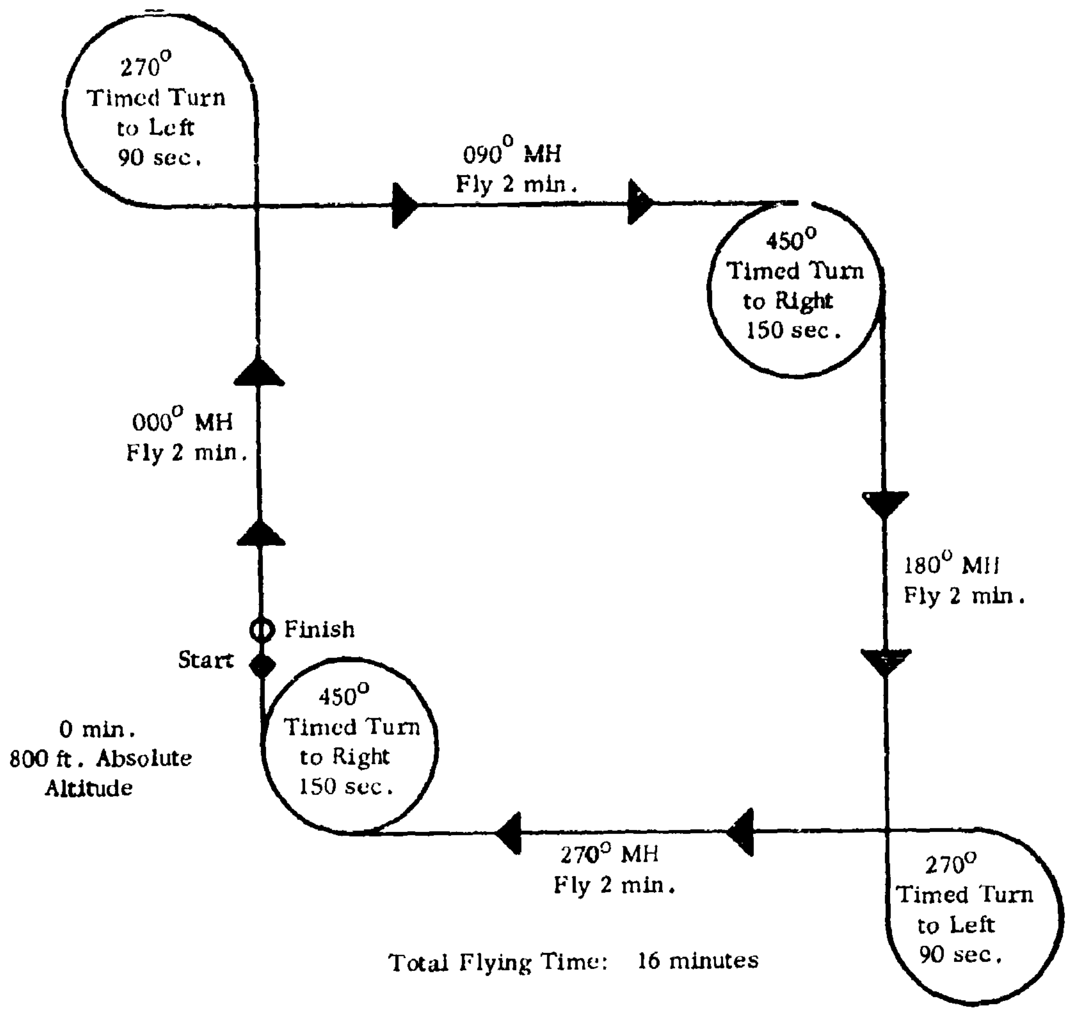
The BRAVO pattern was derived from the U. S. Navy's "Charlie" pattern, used during WW II to train pilots to fly instruments and qualify for the Standard Navy instrument card. A further discussion of the pattern may be found in the Navy All-Weather Flight Manual (16).

Flying the BRAVO pattern during this study was not considered as complex as flying by instruments alone, mainly because the pilot was allowed to see out of the aircraft to cross-reference his flight instruments. The performance criteria for the BRAVO pattern, therefore, appeared achievable and realistic as a performance measure for this study.

A movie camera was mounted in the aircraft (Figure 2) to take pictures of the flight instrument panel at the rate of one frame per second (shutter speed of 1/250 second) during each BRAVO pattern flown. A turn-and-bank indicator, sweep second timer and clock were installed (Figure 2) for the pilot and performance observer to use during each flight pattern.

<u>Observation of Ground Targets</u>. The pilot-subject was given an inflight task of periodically observing and recording the configuration, observation time, and orientation of a ground target (Figure 1), while simultaneously flying the BRAVO pattern (Figure 5). The target was painted international fluorescent orange, which made it distinguishable at an expected slant range of two miles at an altitude of 800 ft.; it was identifiable at just under a mile. Pilot performance scoring was accomplished after the flight by comparing the ground crew's log with the pilot's written observations.

<u>Response/Reaction Time Measures</u>. The pilot's response and reaction times were measured 30 to 40 times during each flight. To accomplish the reaction time measurement, the pilot was alerted ahead of time that he was to receive a continuous tone 2000 CPS signal in his headset. At the onset of the signal, the pilot responded by pressing the trigger switch on his cyclic control, which stopped the signal and an elapse timer accurate to 1/100 second. The 2000 CPS signal was selected because it was not masked by the aircraft's ambient noise levels, because it did not resemble any existing aircraft signal or interfere with normal or emergency signals, and because it did not interrupt communications.



PERFORMANCE CRITERIA:

1. Hold Heading within $\pm 5^{\circ}$
2. Hold Altitude within ± 50 ft.
3. Hold Airspeed within ± 5 knots
4. Fly Precision Timed Turns of 3° per/sec. within ± 2 seconds accuracy

Figure 5. BRAVO Precision Flight Pattern

The response-time measures were taken the same way, except that the pilot did not receive any prior warning of the signal. In both cases the pilot was engaged in a primary task of flying the aircraft, which required his right hand to be on the cyclic control. Figure 2 illustrates the control box which the performance observer used during each flight to control the camera, elapse timers and pilot response time signal.

Post Flight Debriefing. The pilot was debriefed after each flight for an appraisal of the environmental conditions, the clothing and survival equipment worn, and other flight conditions. Selected questions, which encouraged objective answers, were grouped on separate cards and given to the pilot to read and answer. All his comments were tape recorded.

The pilot interview was considered structured but open-ended. The interviewer remained silent during most of the recording to minimize any biasing of the pilot's responses to the questions. The pilot, in turn, was free to select question cards in any order of importance to him and could spend as much time as he wished to respond to the questions.

PHYSIOLOGICAL MEASUREMENTS AND EQUIPMENT.

Heart Rate. Measurement of the pilot's heart rate was taken by the physiological observer before, during and after each flight. Two silver electrodes were applied to the skin of the pilot's chest at the sternum (Figure 6). Two wire leads (reference and recorder) connected the electrodes to a battery-powered oscilloscope and to a small (3 1/2 lb.) electrocardiographic recorder (Figure 3). The observer manually recorded pilot heart rate readings from observations of the oscilloscope every five minutes. The portable recorder made a continuous, permanent heart electrocardiograph record which was analyzed after each flight.

A "breadboard" portable telemetry unit was installed in the aircraft to assess the capability of the hardware to transmit both an electrocardiograph signal of the pilot's heart rate and the rectal temperature (Figure 6). The system was installed as a redundant heart rate monitor, primarily for test purposes.

Body Core Temperature. A rectal thermister probe worn by the pilot during each flight was wired to the temperature display at the physiological observer's station (Figure 3) to enable inflight body-core temperature measurements every five minutes.

Skin Temperature. One skin temperature sensor was worn on the inboard position of the upper thigh of the pilot during each flight. Studies by Teichner (11) indicated that one sensor placed in this position could provide an overall assessment of mean body surface temperature. A wire from the sensor was connected to the temperature display at the physiological observer's station (Figure 3) to enable inflight readouts every five minutes.

Weight Loss. The pilot-subjects were weighed nude just before and after each flight to determine possible weight losses due to perspiration. The scale was accurate to the nearest five grams (approximately .01 lb.).

AIRBORNE ENVIRONMENTAL MEASURES. Wet Bulb (WB), Dry Bulb (DB) and Globe Temperature (GT) thermisters were positioned in the cockpit just forward of the pilot (Figure 2). Additional DB sensors were mounted at the crown of the cockpit, shaded from the sun, and at two locations on the physiological observer's seat (passenger compartment).

A Wet Bulb Globe Temperature (WBGT) Index was used as the overall measure of the total heat stress imposed on the subjects. WBGT index is computed as follows, as per TB MED 175 (14):

$$\begin{aligned} \text{WBGT} = \; & 0.7 \text{ Wet Bulb Temperature } (^{\circ}\text{F}) \\ & +0.2 \text{ Black Globe Temperature } (^{\circ}\text{F}) \\ & +0.1 \text{ Dry Bulb Temperature } (^{\circ}\text{F}) \end{aligned}$$

Environmental measures were taken simultaneously with physiological measures at least every five minutes of flight.

GROUND METEOROLOGICAL MEASURES. WB, DB and GT measures were taken on the ground immediately before and after each flight to obtain comparative measures of WBGT for each flight. Measures of WB and DB were also taken periodically with an electric psychrometer as a cross-check on the temperature measures taken for the WBGT Index. Standard Relative Humidity (RH) was computed from the psychrometer data.

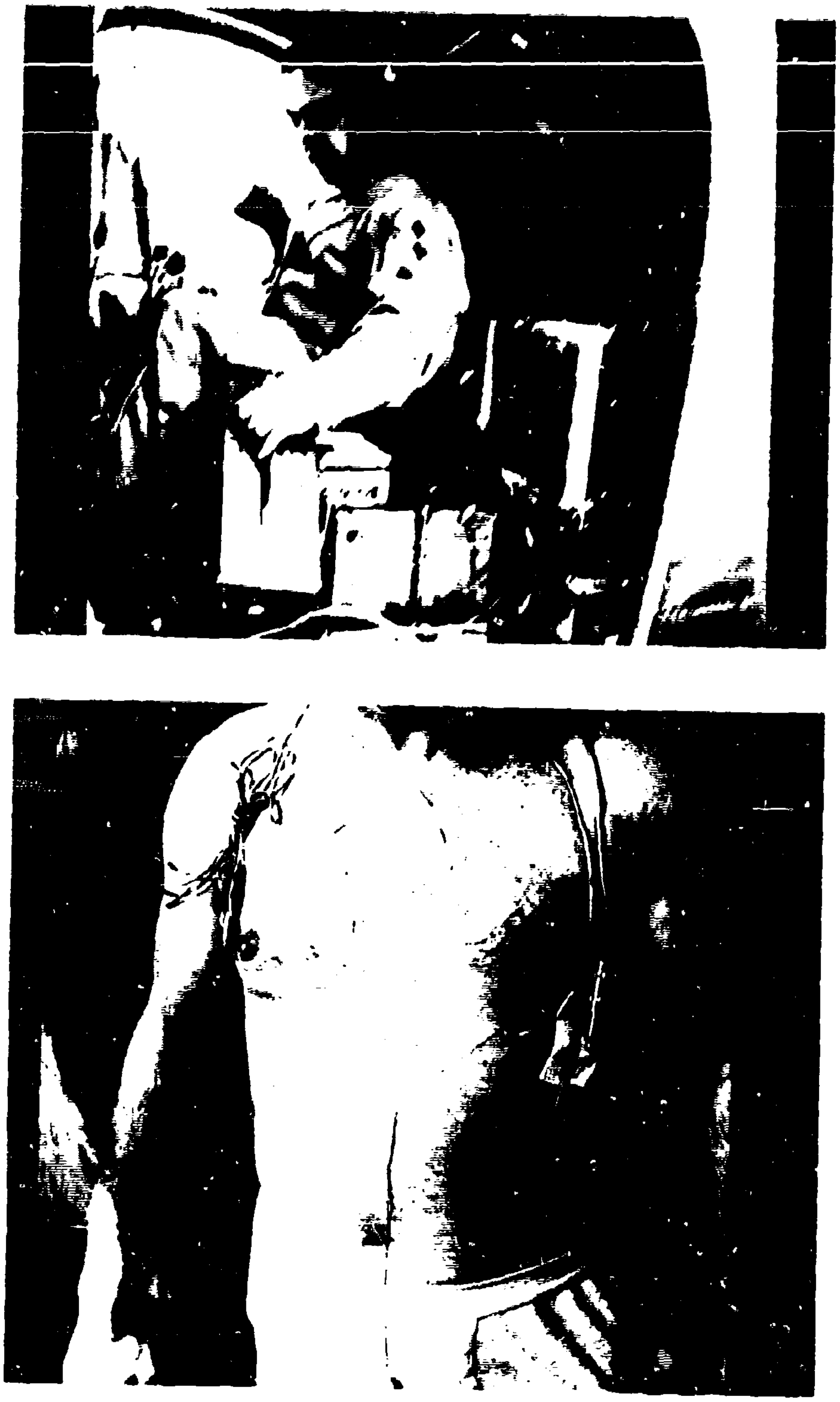


Figure 6. Above: Physiological observer viewing portable oscilloscope to determine pilot heart rate. A partial view of telemetry transmitter installation is shown in foreground.

Below: Mounting of skin thermisters for measurement of heart rate.

The official DB, Dew Point (DP), wind and cloud cover, as reported by the Fort Rucker (Cairns Field) Flight Meteorological Services, were recorded for each test flight as a cross-reference for measures obtained by the study team.

DATA REDUCTION AND ANALYSIS All physiological and psychological performance measures taken on each pilot-subject were obtained simultaneously with the crew station environmental measures.

A photopanel exposure was made of the flight and engine instruments every second during each 16-minute BRAVO flight pattern. Usually, two or three patterns could be flown during each hour of flight. This data was reduced, recorded and compared to pilot physiological and psychological performance and environmental measures taken approximately every five minutes of flight. Because of the large volume of information generated during the study, a pilot study was initially performed in which different time intervals of collected data were sampled to determine the degree of performance changes and trends during these intervals. Ten-second intervals were selected as optimum for the photopanel data. Extrapolations were made between the five-minute intervals of data collected from the physiological and environmental measures to obtain corresponding information for each ten-second photopanel time frame.

For the purpose of recording and processing the data, this time frame was identified as a "line entry." A line entry represented all inflight performance, physiological and temperature measures recorded at ten-second intervals during each 16-minute BRAVO flight pattern.

An equation was devised to represent an overall measure of pilot performance while he was accomplishing his primary task, flying the BRAVO pattern. This performance value could then be compared with the physiological and environmental measures occurring in the same time frame. The following formula was developed for computing the measure of pilot performance (P_1) for each line entry of the flight data:

$$P_1 = 100 - (\text{absolute airspeed error} + \text{absolute altitude error} + \text{absolute heading error} + \text{absolute } \triangle \text{ torque})$$

where 100 = an arbitrary scoring value for perfect performance. The absolute (abs) values were obtained by comparing the following precision flight requirement values with the actual aircraft values achieved:

Airspeed (A/S)	= 80 knots
Altitude (alt)	= 800 feet absolute altitude (1100 feet indicated altitude at Fort Rucker, Ala.)
Heading (hdg)	= as per the BRAVO flight pattern (Figure 5)
Torque	= the absolute difference of the value of present torque and the previous value of torque for any two sequential time periods. In the special case of the initial value of torque for each pattern, $\triangle$ torque was the absolute difference between 50 PSI and the value of torque. The value of 50 was chosen as respresentative of a realistic power setting for the aircraft and flight conditions. A variation of ± 2 PSI was considered normal for the power/load/airspeed operation of the OH-6A during the BRAVO pattern.

The numerical version of the formula for measurement of performance is as follows:

$$P_1 = 100 - \text{abs } (80\text{-A/S}) - \text{abs } (1100\text{-alt}) - \text{abs } (\text{hdg error}) - \text{abs } (\triangle \text{ torque}).$$

The term "with limits applied" as used in this report references a variation of the P_1 value which has been computed with the tolerances allowed by the BRAVO pattern performance criterion (Figure 5). The term "without limits applied" describes the actual performance (P_1), discounting the performance criterion tolerances.

To enable a comparison of the P_1 changes with changes in physiological and environmental variables, the data was organized in a form to enable the analyst to make use of the Ballistic Research Laboratories (BRL) Stepwise Multiple Regression Computer Program developed by Breaux, et al. (1). The candidate model equation used by this program considered all variables to the fifth power and then eliminated those which did not meet the criteria of a .001 level of significance. The candidate model for this experiment was described as:

$$P_2 = V1 + a_1V2 + a_2V2^2 + a_3V2^3 + a_4V2^4 + a_5V2^5 + a_1V3 + a_2V3^2 + a_3V3^3 + a_4V3^4 + a_5V3^5 + \ldots a_nV10^5.$$

where:

Factors	Reference Literature Source of Standards
V1 = Constant	Breaux, Campbell, Torrey (1)
V2 = 73 - Wet Bulb Temperature Value	AFSCM 80-3 (12)
V3 = 100 - Globe Temperature Value	AFSCM 80-3 (12)
V4 = 90 - Dry Bulb Temperature Value	AFSCM 80-3 (12)
V5 = 85 - WBGT Index Value	Minard (8), Yaglou (17)
V6 = 98.9 - Rectal Temperature Value	DuBois (2)
V7 = 94.5 - Skin Temperature Value	Hall & Klemm (3), DuBois (2)
V8 = Base Heart Rate-Heart Rate Value	Plattner (10)
V9 = 69 - Dew Point Temperature Value	AFSCM 80-3 (12)
V10 = 70 - Relative Humidity Temperature Value	AFSCM 80-3 (12)

From the candidate model equation, the program derived an equation which provided the above variables (V1 - 10) with the proper exponents and coefficients to best describe (or best fit) the performance shown by the pilots. This program also provided a value for each line entry of performance as given (P_1) and as computed using the equation derived by the program (P_2). The difference between the value of P_1 and P_2 was known as the residual value. Theoretically, the ideal residual equaled zero, thereby substantiating the predicting capability of the derived equation P_2

Computer analysis runs were made to determine the "best fit" performance equation P_2, both with and without crew performance limits applied for the following conditions: 1) AM flights, 2) PM flights, 3) All flights, and 4) those flights having a WBGT index higher than 85°F.

The computer was also programmed to provide means, standard deviations, frequency counts and the values of N for other computations which were to be performed manually for the study.

RESULTS AND DISCUSSION

MEASURES OF PILOT PERFORMANCE WITH TEMPERATURE CHANGES. Measured data from all flights with a WBGT Index of greater than 85°F were grouped together as "hot" flights and compared with other flights by time periods (Table 1).

Flight Time Periods*	Mean Perf. (P_1) (all subjects)	Sigma	Total Flights	Total Patterns	Line Entries
Morning	85.94	20.32	4	7	612
Afternoon	87.53	23.[illegible]0	21	76	4452
Hot	81.196	25.688	6	24	1880
All Flights	87.33	22.785	25	83	5064

TABLE 1. Comparison of Pilot Performance on Hot Flights with Other Flights

* Table 4 provides a summary of crew station temperatures associated with each flight time period listed in Table 1.

Even though no significant difference in performance was found, the above data sample clearly suggests that when the WBGT Index increases above 85^{o}F, performance decreases and variability increases.

The change in performance with temperature changes was even more apparent when the mean performance flight data of pilots L and C, who completed all required flights, were compared with WBGT Indexes which were either greater than or less than 85^{o}F:

Mean Performance (WBGT $>$ 85^{o}F, 1695 line entries) = 80.99

Mean Performance (WBGT $<$ 85^{o}F, 4159 line entries) = 89.00

All flights were reviewed to determine associated temperatures when pilot performance (P_1) fell below an arbitrary value of 50. Table 2 summarizes mean temperatures from four flight patterns in which the mean low P_1 = 42.44 and the flight having the lowest performance score of 35.83.

P_1 = 42.44	P_1 = 35.83
WB = 76.8 GT = 110.4 DB = 100.5 RT = 99.5 WBGT = 85.9	WB = 94.4 GT = 118.6 DB = 103.1 RT = 99.9 WBGT = 98.1

TABLE 2. Associated Temperatures when Pilot Performance (P_1) Fell Below 50.

Of the days in which both AM and PM flights were scheduled and flown by the same pilot, wearing the same clothing/equipment configuration, only one day's matching of flights yielded enough performance data to be reportable -- the rest were incomplete because of weather, inadequate film, flight cancellation, etc. Table 3 summarizes the flight performances versus temperatures for pilot-subject C, wearing the same clothing configuration, flying both an AM and PM flight on 4 September 1966.

	AM Flight No. 18			PM Flight No. 20		
	Mean Perf.(P_1)	Perf. Var.(SD)	Mean WBGT	Mean Perf.(P_1)	Perf. Var.(SD)	Mean WBGT
First Flight Pattern	84.54	18.94	78.9	85.42	19.18	82.1
Second Flight Pattern	89.25	12.81	80.8	80.77	22.71	83.2
Total Flight	86.52		79.7	84.05		82.45

TABLE 3. Comparison of Pilot Performance and Environmental Temperatures for Matched Flights

Though one sample of data (Table 3) cannot be used to predict, it does relate to other findings (Tables 1, 2 and 6) showing a tendency toward a decrease in performance as temperature increases and an increase in performance variability as temperature increases.

Table 4 provides an overall listing of some of the inflight measured performance and temperature data summarized from each flight flown during the study.

Flt. No. and Pilot	Scored Flt. Patterns	Line Entries	Perf# (P_1)	A/S Error# (knots)	Alt. Error# (feet)	Heading Error# (degrees)	Delta Torque# (PSI)	Wet Bulb Temp. °F	Globe Temp. °F	Dry Bulb Temp. °F	WBGT Index °F	Rectal Temp. °F
MORNING FLIGHTS												
1C	1	74	76.77	3.00	1.29	36.98	1.67	67.85	92.43	82.45	74.23	99.23
6L	2	188	79.11	2.62	2.01	31.83	1.42	77.29	99.55	93.13	83.32	99.36
18C	2	180	86.52	2.80	1.88	21.28	2.18	74.72	93.61	86.73	79.70	99.30
21L	2	170	96.88	.66	1.18	7.22	3.03	73.58	94.84	88.88	79.36	98.89
AFTERNOON FLIGHTS												
* 7C	5	366	55.54	4.04	2.06	57.43	1.82	77.53	111.60	100.66	86.65	99.49
* 9L	4	338	93.49	1.72	1.65	11.92	3.16	93.15	110.92	98.71	97.26	99.50
* 10C	4	295	75.79	2.84	.55	34.91	2.51	92.36	106.93	97.96	95.83	99.31
* 11B	2	185	83.09	1.75	2.82	27.95	1.92	86.98	100.16	97.02	90.62	99.85
* 15C	5	375	85.76	2.51	1.94	21.31	2.79	78.05	114.90	101.41	87.75	98.90
* 16L	4	321	96.05	2.47	1.60	5.68	3.18	76.29	109.43	100.04	85.30	99.66
2G	2	189	91.31	4.06	2.99	18.80	4.04	69.91	102.69	91.51	78.62	99.69
3C	0	Cancelled because of aircraft malfunction.										
4L	2	207	92.40	2.61	3.50	11.63	2.91	73.95	108.91	97.04	83.25	99.62
5C	4	258	61.49	2.74	2.04	55.92	1.64	74.84	103.38	98.54	82.91	99.47
8L	0	Cancelled because of rain.										
12L	4	343	91.91	1.81	1.83	14.56	3.45	74.45	109.73	99.18	83.98	99.26
13C	4	334	90.76	2.24	1.46	15.05	2.09	74.40	102.72	99.18	82.54	98.26
14L	3	260	97.52	1.50	1.66	6.05	2.12	74.37	107.86	100.60	83.69	99.72
17C	1	80	76.31	2.78	2.00	31.89	2.71	73.69	96.44	94.85	80.35	99.50
19L	4	309	95.71	2.68	2.20	6.71	4.48	75.63	101.82	92.97	82.60	99.26
20C	2	251	84.05	3.27	2.57	25.74	2.43	74.14	104.98	95.44	82.43	99.22
22L	0	Incomplete performance data because of movie camera malfunction.										
23C	3	237	84.14	2.39	1.76	23.87	2.88	73.49	107.93	96.81	82.71	99.04
24L	4	340	97.40	1.00	1.25	4.25	3.61	74.45	111.19	101.73	84.53	99.81
25B	5	373	73.06	1.83	1.46	42.36	1.91	70.68	105.19	98.50	80.37	99.70
26L	4	340	97.38	.62	1.12	4.42	3.59	72.34	100.06	92.05	79.85	99.29
27C	3	266	81.39	3.05	2.73	22.24	2.48	70.19	105.78	94.72	79.76	99.30
28L	4	322	95.70	2.91	1.65	5.24	4.82	71.10	111.02	99.75	81.95	99.43
29B	5	342	77.32	3.03	1.45	34.02	1.76	69.44	99.74	94.49	78.00	99.67

* Indicates Hot Flights, >85°F WBGT. # With Performance Limits Applied.

TABLE 4. Means of Performance and Environmental Measures

CORRELATION (r) OF PILOT PERFORMANCE FACTORS WITH PHYSIOLOGICAL AND ENVIRONMENTAL TEMPERATURES. Individual pilot performance measured during the study was compared with recorded WBGT Index and physiological measures occurring simultaneously. Tables 5 and 6 summarize the resulting correlation (r) values for each pilot.

Significant differences from zero were determined at the .01 and .05 level for each pilot using the means of repeated measures from each flight pattern (Tables 5 and 6).

A search of the literature did not provide a clear basis to make a valid assessment of the importance of physiological correlation values. Values of r = .1000 for example, may be quite significant in view of the fact that a small change in Rectal Temperature can be critical. The results might be interpreted as trends and many appear to produce the expected results. For example:

1. For all subjects, WBGT appeared to have a positive correlation with heart rate (Table 5). This positive correlation would have been predictable according to results reported by DuBois (2), Hall (3) and others.

2. The negative correlation between performance and WBGT for pilots L and C (Table 5) might be considered a trend since these pilots flew the most flights and, therefore, represented a larger sample of behavior.

3. Three of the four subjects showed a negative correlation between performance and skin temperature (Table 5). The strong r of -.97 for pilot G should not be overinterpreted because it represents only one flight of data.

Comparative Measures	Pearson Correlation Values (r)# for Mean Flight Pattern Scores			
	Pilot L (n = 41)	Pilot C (n = 35)	Pilot B (n = 12)	Pilot G (n = 2)
Pilot Performance (P_1) vs. Skin Temperature	.5031**	-.0069	-.3467	-.9730
Pilot Performance (P_1) vs. Rectal Temperature	.0783	-.5453**	-.1035	.3145
Pilot Performance (P_1) vs. Heart Rate	-.4503**	.0473	.0124	.3335
WBGT vs. Skin Temperature	.2072	.2520	.2790	-.3887
WBGT vs. Heart Rate	.3640*	.8167**	.9307**	.6856
WBGT vs. Rectal Temperature	.2686	.1588	.8112**	-.3754

Calculations are based on summaries of data obtained for each flight pattern of all flights (Table 4) for each pilot. Pilot G flew only one flight.

Minus (-) r indicates that as temperature increased, performance decreased.

* Significant at the .05 level.

** Significant at the .01 level.

TABLE 5. Correlations of Pilot Performance and Physiological Measures

The Pearson correlation analysis of performance (P_1) and temperatures did not fully substantiate the predictor equation results determined by the stepwise multiple-regression program summarized in Tables 7 and 8. This difference probably occurs because the Pearson is a test of linear relationships, while the multiple-regression program defined a curvilinear relationship between all measures.

Measured Condition		Pearson Correlation Values (r) for Mean Flight Pattern Scores		
		Pilot L (n = 41)	Pilot C (n = 35)	Pilot B (n = 12)
Performance vs.	Wet Bulb	-.0037	-.1461	.2339
" "	Globe	.2039	.3440*	.0602
" "	Dry Bulb	.2198	-.2273	-.2141
" "	WBGT	-.1394	-.1800	.1867
Sigma Perf. vs.	Wet Bulb	.2475	.0439	-.3094
" "	Globe	-.2144	-.0946	.2574
" "	Dry Bulb	-.2249	.1386	.2220
" "	WBGT	.1055	.0128	-.2400
Delta A/S vs.	Wet Bulb	.0885	.2010	-.2855
" "	Globe	-.2557	.3103	-.0204
" "	Dry Bulb	-.2521	.0204	-.2726
" "	WBGT	-.0757	.2434	-.2957
Delta Alt. vs.	Wet Bulb	.0619	-.4455**	.6364*
" "	Globe	.2341	.0699	-.2432
" "	Dry Bulb	.0523	-.3251*	-.0349
" "	WBGT	.0819	-.3280*	.5699
Heading Err. vs.	Wet Bulb	.2263	.1612	-.2398
" "	Globe	-.2629	.1240	.1502
" "	Dry Bulb	-.2528	.2560	.2038
" "	WBGT	.0602	.1800	-.1934
Delta Torque vs.	Wet Bulb	-.1794	.2047	.0460
" "	Globe	.5940**	.6706**	.5741
" "	Dry Bulb	.3145*	.2549	.6769*
" "	WBGT	.0535	.3321*	.1883

The anticipated correlation (r) relationships at the start of the study were as follows:

Performance:	negative value of r, temperature up, performance down.
Sigma Perf.:	positive value of r, temperature up, Sigma Perf. up.
Airspeed:	positive value of r, temperature up, Delta Airspeed up.
Altitude:	positive value of r, temperature up, Delta Altitude up.
Heading Error:	positive value of r, temperature up, Heading Error up.
Delta Torque:	positive value of r, temperature up, Delta Torque up.

Pilot G was not listed because of insufficient data.

* Significant at the .05 level.

** Significant at the .01 level.

TABLE 6. Correlations of Pilot Performance (P_1) Factors and Environmental Temperatures

REGRESSION CORRELATION ANALYSIS OF PILOT PERFORMANCE VS. ENVIRONMENTAL FACTORS. Tables 7 and 8 summarize the computer analysis runs which established between all data entry measurements of the study the appropriate "best fit" predictor performance equation (P_2), both with and without crew performance limits applied (described in Method Section).

The stepwise multiple-regression solution of the effects of various temperatures upon performance was an attempt to derive a predictor equation for performance based on environmental temperatures. It would have been most satisfying if the solution for each condition of environmental temperatures had provided a linear equation with each variable included; but, in fact, each condition produced a different equation. The equations which applied limits to the performance measures were quite similar to the equations for the same conditions without limits, and the similarity served to verify the equations.

Performance Equations Without Performance Limits	Performance Equations With Performance Limits
1. All Flights: $P_2 = 94.218 + 4.118WB - .277WB^2 + .179GT^2 + .011GT^3 + 2.629DB - .171DB^2 - .028DB^3 - .454WBGT^2 - .016WBGT^3 + 3.463ST - .353ST^2 - .116ST^3 + .072HR + .009HR^2 + .00007HR^3 - 1.572DP - .080DP^2 + .002DP^3 + .391RH$ *Shortened Form: $P_2 = 94.5 + 4.118WB + 2.629DB + 3.463ST - 1.572DP$	1. All Flights: $P_2 = 101.518 + 3.995WB + .272WB^2 - .286GT + .194GT^2 + .012GT^3 + 2.172DB - .197DB^2 - .026DB^3 - .408WBGT^2 - .013WBGT^3 + 3.178ST - .346ST^2 - .119ST^3 + .310HR + .010HR^2 - .0001HR^3 - 1.373DP - .076DP^2 + .002DP^3 + .182RH + .0002RH^3$ *Shortened Form: $P_2 = 101.518 + 3.995WB + 2.172DB + 3.178ST - 1.373DP$
2. Morning Flights (WBGT $< 85^0$F): $P_2 = 76.179 - .375WB^2 + 8.751GT + 1.673GT^2 + .094GT^3 + 30.763RT - .092DP^2 - 500.571RT^5$ *Shortened Form: $P_2 = 76.179 + 8.751GT + 1.673GT^2 + 30.763RT - 500.571RT^5$	2. Morning Flights (WBGT $< 85^0$F): $P_2 = 77.702 + 9.162GT - 1.681GT^2 - 73.039RT^2 - .087DP^2 - .00044RH^3 - 623.55RT^5 - .092GT^3$ *Shortened Form: $P_2 = 77.702 + 9.162GT - 1.681GT^2 - 73.039RT^2 - 623.55RT^5$
3. Afternoon Flights: $P_2 = 67.025 + .423WB^2 + .006WB^3 - .412GT + .382GT^2 + .020GT^3 + 2.459DB - .208DB^2 - .031DB^3 + 6.722WBGT - .549WBGT^2 - .027WBGT^3 + 2.955ST - .552ST^2 - .156ST^3 + .247HR + .011HR^2 - .0001HR^3 - 1.758DP + .00005DP^3 + .0004RH^3$ *Shortened Form: $P_2 = 67.1 + 2.459DB + 6.722WBGT + 2.955ST - 1.758DP$	3. Afternoon Flights: $P_2 = 78.378 + .379WB^2 + .006WB^3 - .479GT + .353GT^2 + .019GT^3 + 2.528DB - .183DB^2 - .028DB^3 + 5.798WBGT - .485WBGT^2 - .026WBGT^3 + 2.53ST - .528ST^2 - .149ST^3 + .242HR + .010HR^2 - .0001HR^3 - 1.556DP + .027DP^2 + .0003RH$ *Shortened Form: $P_2 = 78.378 + 2.528DB + 5.798WBGT + 2.53ST - 1.556DP$

*Shortened forms of predictor equations are provided for ease of reader interpretation and to highlight the more prominent factors contained in the performance equation. It was derived by arbitrarily dropping all factors with a coefficient of less than 1.0.

TABLE 7. Predictor Performance Equations

Performance Equations with Performance Limits
4. Hot Flights (WBGT $> 85^0$F): $P_2 = 187.828 + .5668GT - 1.590DB + .2043WBGT^2 + 526.03RT + 848.976RT^2 + 439.213RT^3 + 9.7947ST - 5.3511ST^2 - 1.2024ST^3 + 1.5525HR + .0849HR^2 - .0029HR^3 - .2653RH^2 + .0114RH^3$ *Shortened Form: $P_2 = 187.8 - 1.6DB + 526RT + 849RT^2 + 439RT^3 + 9.8ST - 5.4ST^2 - 1.2ST^3 + 1.55HR$
5. All Flights with RT, ST and HR out: $P_2 = 68.338 + .2616WB^2 - 1.0346GT + .1558GT^2 + .0104GT^3 + 2.2592DB - .2091DB^2 - .0295DB^3 + 5.4089WBGT - .4351WBGT^2 - .0153WBGT^3 - 1.043DP - .0432DP^2 + .00099DP^3 + .2777RH$ *Shortened Form: $P_2 = 68.4 - 1.0GT + 2.3DB + 5.4WBGT + 1.0DP$

*Shortened forms of predictor equations are provided for ease of reader interpretation and to highlight the more prominent factors contained in the performance equation. It was derived by arbitrarily dropping all factors with a coefficient of less than 1.0.

TABLE 8. Predictor Performance Equations, Special Conditions

Equation 2 for the cool (morning) flights (Table 7) emphasized the importance of the Globe Temperature and Rectal Temperature and assigned lesser significance to Wet Bulb Temperatare and Dew Point Temperature. The large coefficients assigned to Rectal Temperature represented moderate values when it was considered that these changes were tenths of a degree while, in general, the other values changed by whole degrees during the flight investigated.

The flights which were flown under extremely hot (WBGT Index $> 85°F$, Equation 4, Table 8) conditions also emphasized Rectal Temperature and added Skin Temperature, Dry Bulb Temperature and Heart Rate while assigning a lesser significance to Globe Temperature. This equation also considered WBGT Index and Relative Humidity and dropped Wet Bulb Temperature and Dew Point Temperature.

The afternoon series of flights (Equation 3, Table 7), which included the "hot" flights, assigned importance to Dry Bulb Temperature, WBGT Index, Skin Temperature, and Dew Point Temperature. Heart Rate and Relative Humidity were also considered as contributing to the value of performance.

The total solution of all flights (Equation 1, Figure 7) listed Wet Bulb Temperature, Dry Bulb Temperature, Skin Temperature and Dew Point as the major variables and Globe Temperature, WBGT Index, Heart Rate, and Relative Humidity as contributing variables.

The final equation in this group (Equation 5, Figure 8) considered all of the flights' data but did not compute coefficients for the physiological variables (Rectal temperature, Skin temperature and Heart Rate). The results were similar to those for the total flights (Equation 1) with greater importance placed on Globe Temperature and WBGT Index, while Wet Bulb Temperature was considered less important that it was in the total flight equation.

EFFECT OF TURBULENCE ON PILOT PERFORMANCE. There was a question of whether the difference in performance between the "cool" and "hot" flights was perhaps due to the turbulence caused by the heating of the ground. Seven of the flights had a notation by the observer that there was moderate turbulence during the flight.* These flights were statistically compared with flights which had no such notation but which had the same pilot and were matched as closely as possible for equal number of line entries and for equal WBGT values (see Table 9 for a summary of the results).

FLIGHT	P_1 (Limits Applied)	SD	Line Entries	t
10C*	75.79	24.88	295	3.6888
5C	61.49	39.00	258	
15C*	85.76	18.94	375	11.1826
7C	55.54	32.99	366	
16L*	96.05	4.97	321	5.2246
12L	91.91	9.54	343	
19L*	95.71	5.80	390	-3.2540
26L	97.38	3.38	340	
20C*	84.05	20.22	251	-0.0600
27C	84.19	17.21	266	
23C*	84.14	19.34	237	-0.0216
27C	84.19	17.21	266	
24L*	97.40	3.46	340	-0.2727
14L	97.52	4.07	260	

*Turbulence noted by observer and pilot.

TABLE 9. Comparison of Pilot Performance During Turbulent and Non-Turbulent Flights

* Standard inflight terminology as used by the joint services and defined in TM 1-300 (15) was used to report the degree of turbulence encountered during each flight. These classifications of turbulence are selected according to the effect of the turbulence on the aircraft.

The negative values of t are the cases in which the performance is better under the "hot" non-turbulent conditions. There was only one case (Flight 19) of seven in which there was an apparent disadvantage due to turbulence. During this flight turbulence was noted as increasing from moderate to "severe." The difference in performance, as tested by the t test was significantly better than chance at the .01 level of confidence.

It can be seen that in both cases performance generally varied more under smooth air conditions than it did under turbulent conditions. One possible reason for the improved performance during turbulence is that more attention is required of the pilot.

Additional experimental evidence of the small effect of light and moderate turbulence upon the performance of experienced pilots in helicopters has been provided in simulator studies by Nicholson, et al. (9), and Hornick and Lefritz (5). The results indicated that pilot performance was not significantly affected by gust loadings to 15K and/or 0.20 RMS G intensities.

VARIABILITY OF PILOT PERFORMANCE. The mean performance for each pilot during the entire study was as follows:

Pilot	Mean Perf. (P_1) (with limits)	SD	Total Line Entries
L	94.44	9.43	3139
C	78.04	29.49	2715
B	76.74	29.44	900
G	91.43	15.97	189

TABLE 10. Performance Variability Among Pilots

It can be seen that there were differences in the mean performance of the pilots who flew in this study. This difference was made more pronounced by the methods of scoring performance during the BRAVO precision flight patterns. While all the pilots flew well, it was observed during the flights and in reviewing the scoring that techniques of flying affect performance. The pilot who used a method averaging out aircraft attitude, heading and altitude changes during the BRAVO flight pattern, scored lower than the ones who corrected immediately to the desired position. This variability seems to fit the normal expected variation of human performance.

WEIGHT LOSS. The value of the mean water loss for all pilots in the experiment was 1.216 lbs. per flight; the standard deviation was given as .7734. The range of these water losses varied from .154 lbs. to 2.464 lbs., of which pilot L had the most variability. Because of human variability in this area, it seemed more meaningful to consider each pilot separately regarding water loss versus performance correlation. Pilot G was not listed because of insufficient data. A summary these calculations are provided in Table 11.

Pilot	Mean Perf. (P_1)	Mean Water Loss	Correlation r	Line Entries
L	94.21	1.408	r = .4232	3139
C	78.04	1.159	r = .1141	2716
B	77.82	1.075	r = -.9926	900

TABLE 11. Comparison of Pilot Performance and Water Loss

For pilot B, the correlation was nearly perfect, but the sample size was only three flights as compared with 10 and 12 flights for the other pilots.

INTERACTION OF TEMPERATURE, PERFORMANCE AND CLOTHING. Each clothing configuration used by the pilots during the study was compared with their associated performance (P_I) while wearing the clothing. The results are summarized in Table 12.

Clothing Configuration	No. Flights	Mean Perf. (P_I)	Computer Line Entries
A	8	86.05	2277
B	8	85.88	2183
C	9	82.76	2162
D	1	95.70	322

TABLE 12. Comparison of Pilot Performance and Clothing Configurations

The performances using clothing configurations A and B, both of which include body armor, are for all purposes identical. The performance using clothing configuration C, which does not include armor, is somewhat lower than the others but not significantly so. Performance wearing clothing configuration D is not a true representation of this configuration as it refers to only one pilot and one flight; hence, even though the performance is better than with any other configuration, it cannot be considered as a preferred configuration without further testing. The pilots' subjective comments regarding the D clothing configuration indicated it was completely unacceptable.

TARGET IDENTIFICATION TASK. The data was analyzed for variations in pilot performance due to individual differences, clothing differences and fatigue, and differences in environmental temperature. A total of 348 target displays were presented to the pilots during 22 flights providing usable data. Of the 348 target displays, 228 were correctly identified, 89 were incorrectly identified and 31 were not detected. During the 22 flights the pilots flew five flights with A, six with B, ten with C and one with D clothing configurations.

The data were analyzed using WBGT Index as the environmental measure with a mode of 85°F. The flights were broken into two groups, AM and PM. No AM flights had a WBGT greater than 85°. The results showed that there were no significant differences in pilot performances. There was no significant difference between performance during the first part of the flights and performance during the latter part of the flights. There was a trend indicating a difference in performance due to clothing, but this was not significant at the .1 level.

The PM flights show a greater number of errors occurring when armor was worn and the WBGT was greater than 85°. In the cases when no armor was worn, the errors occurring in each temperature zone were approximately equal. The results indicate that trends were present but were not significant at the .1 level.

REACTION/RESPONSE TIME MEASURES. Pilot reaction times and response times were measured 30 to 40 times per flight. The range of mean reaction times for all pilots during the study varied from .23 to .63 seconds, with an overall mean of .44 seconds. Response times varied from .41 to 1.21 seconds, with an overall mean of .93 seconds.

Pilot reaction times were taken in a more consistent manner than response time measures; the results contained smaller ranges of values and smaller variability. Only reaction times were, therefore, considered reliable enough to be reported and are summarized in Table 13.

The correlation analysis of the data indicates a trend showing an increase in pilot reaction time as either Rectal Temperature or the WBGT Index increases.

Measured Condition	Pilots **		
	L (n = 9)	C (n = 9)	B (n = 3)
Reaction Time vs. WBGT (seconds)	.436	.124	.994*
Reaction Time vs. Rectal Temp. (seconds)	.220	.380	.993*

* Significant at the .05 level.
** The n values shown for the pilots represent the means of 234 repeated measures from several flights (Pilot G was not listed because only one flight was available for analysis).

TABLE 13. Correlation of Reaction Times with Temperature Measures

COMPARISON OF GROUND AND AIRBORNE WBGT. During the earlier portion of the study it was hypothesized that perhaps a fixed relationship (similar to a standard adiabatic lapse rate of temperature) may exist between the WBGT Index measured at ground level and that measured in the aircraft, assuming that the measurements were taken during the same time period and that the aircraft maintained the same airspeed and absolute altitude, and remained within the local area (5-10 miles). It was hoped that if a reasonably constant relationship did exist, then perhaps ground measurement of cockpit WBGT would help schedule the aircraft for the desired above 85°F WBGT flight conditions.

Unfortunately, no constant relationship could be determined between airborne measurements of WBGT and those taken on the ground. In 18 out of 28 cases compared, the airborne measured WBGT was greater than the WBGT measured on the ground during the same time frame. The range of differences between ground WBGT and airborne WBGT was 4.64 to -15.29. The mean difference was -2.4157 and the sigma was 4.56.

PILOT COMMENTS AND OBSERVATIONS. All of the pilots expressed a desire for improved ventilation in the crew station.

Figure 7 summarizes the rating scale of pilots' judgments of the crew station environment. Their judgments are compared with the actual WB, DB, GT and WBGT Index, as measured during each flight in which the pilot reported a specific rating scale index. During the study, no attempts were made to inform the pilots of how their subjective ratings of crew station environment compared with the actual measured temperatures.

The pilots' ratings of a "cool" or "warm" environment included very large overlaps and very large ranges of each temperature measured. Some flights were actually hotter than others they rated as "hot" or "very hot." If only mean (X) temperature values are considered, Figure 7 indicates that pilot ratings tended to parallel actual increases in Globe and Dry Bulb Temperatures when reporting their estimates of "cool," "warm," "hot" and "very hot." When the environment was judged as "hot," the range of actual temperature was smaller than when the ratings were "cool" or "warm"; however, the number of times "hot" was selected was also less, which could account for the smaller range. "Very hot" was selected only once.

One conclusion which can be drawn from these data is that pilot judgment of cockpit environmental temperature is inconsistent and appears to be unreliable as a means of assessing actual environment.

(Detailed pilot comments regarding clothing and survival equipment fit and problem areas were not considered to be appropriate to this paper, and, therefore, are not presented. These comments can be obtained upon written request to the authors.)

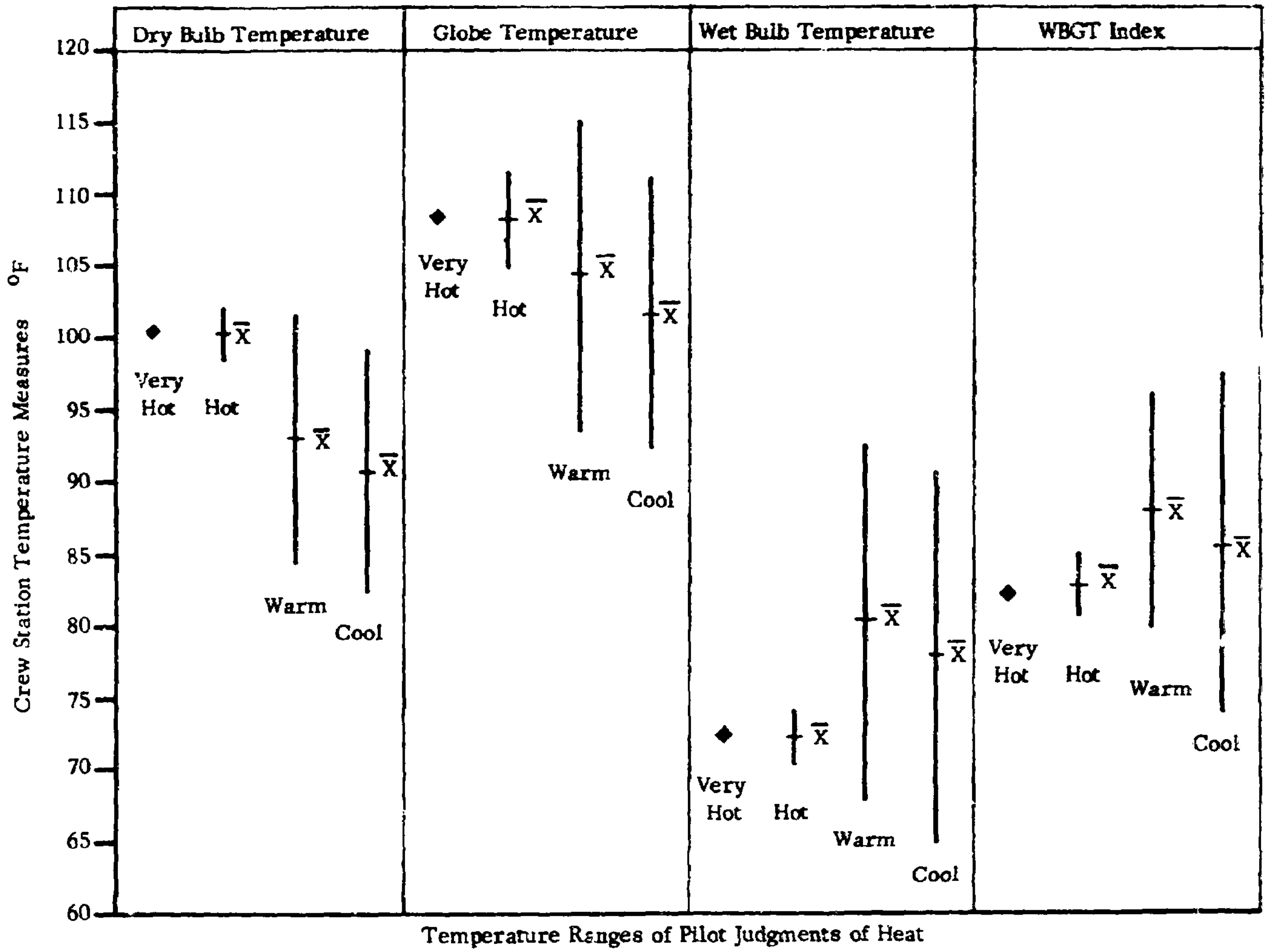


Figure 7. Pilot Judgments of Heat as Related to Crew Station Environmental Temperature Measures

MISCELLANEOUS COMMENTS AND DATA. The following recorded data extracts and comments regarding the crew station environment are provided for general reader interest:

1. During flight (at 800 ft. absolute altitude), the cockpit WBGT Index frequently rose above 90°F and occasionally reached 95°F and 97°F. The highest recorded WBGT Index was 105.1°F (91f, 91:WB 97°F, GT 127.5°F, DB 117°F).

2. DB temperatures taken at the seat reference point (SRP) of the passenger compartment seat measured 110°F-118°F when the cockpit environment measured 102°-103°F. Some of this heat was believed to be radiated heat generated from the engine and transmission.

3. Ground reflected solar radiation appeared to cause rapid increases in overall cockpit DB temperatures when the aircraft was at or passing through 200 ft. absolute altitude. It was not uncommon for the overall cockpit DB temperatures to raise from 90°F to above 110°F within 60 seconds.

4. With the aircraft sitting on the ground with a bright sun and DB of 85°-90°F, cockpit doors and vents closed, the cockpit DB would rise to 155°F, the maximum point on the temperature scale.

5. The old problem of testing enough subjects to get a significant n need not be a limitation in an aircraft. During the two month period of optimum weather for this study 10 to 20 subjects could have been tested, provided a modest increase in the manpower and aircraft resources were made available.

6. If a magnetic tape recording system was substituted for the photopanel technique and many of the manual recording tasks performed by the inflight observers of this study, the data recording and analysis of the flights would have been greatly unburdened and the number of inflight observers could have been reduced.

7. Air velocity measurements of the cockpit taken with a hot wire anemometer were as follows:

Flight Mode	Vent Settings	Probe Position	Rate of air movement, ft/min, at level of: Head	Hip	Toe	Average air movement, ft/min
Slow Cruise (80K)	Vents Closed*	R	30	30	35	32
		C	20	25	50	32
		L	25	25	40	30
	Vents Open	R	160	300	45	168
		C	210	150	50	137
		L	480	110	85	225

Probe position: R = 2" to right of body
C = in mid-body plane, 2" in front of body or between legs
L = 2" to left of body

*The vent closed position was used during this study.

TABLE 14. Cockpit Air Movement Measures

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TECHNICAL EVALUATION

The meeting was opened by the Chairman of the Aerospace Medical Panel of AGARD, Professor Dr. E. A. Lauschner, Brigadier General MC, GAF, who welcomed the participants and outlined the objective of the symposium. He pointed out that the measurement of flight deck workload and its relation to pilot performance was a complex problem of relevance to both the operational commander and his aeromedical counterpart. These topics could not be covered exhaustively during the course of a short meeting, though he considered that the papers to be presented highlighted important aspects of the problem.

The Chairman's opinion was substantially justified during the subsequent one and a half days, when eleven papers were presented to an audience of some ninety-six participants.

Many of the papers presented emphasised the integrative nature of the workload concept, although three were primarily concerned with the effect of specific stresses, such as sleep loss and thermal stress. The importance of that phase in flight when the pilot's task is the most demanding and the consequences of failure the most disastrous, namely approach and landing, was emphasised in at least four papers. Three papers dealt with manipulation of workload and its effect on performance during simulated flight, while three papers described in-flight measurements of possible physiological indicants of workload.

OBSERVATIONS AND RECOMMENDATIONS

Workload

Despite recognition of the great majority of the environmental and task-generated stresses to which the aviator is exposed, the manner in which they interact, like their combined effect upon operational efficiency, is inadequately understood. In order to overcome some of the difficulties associated with an analytic approach to the study of the effect of multiple stresses of the flight environment, the integrative concept of workload has been introduced. It is convenient to divide workload in a temporal manner:

1. Immediate workload, i.e. any workload experienced over a particular short period of time;

2. Duty-day workload, i.e. the summation of the short-term workloads experienced during a working day;

3. Long-term workload, i.e. the summation of duty-day workloads over a sequence of working days.

Measurement of Workload

The study of physiological variables, (such as heart rate or oxygen consumption) which might serve as useful measures of workload, were discussed by several authors. It would appear that these physiological measures, whilst providing an indicant of heightened behavioral arousal and energy expenditure in response to short-term increments in workload, their value, per se, in the evaluation and estimation of workload over longer time periods awaits substantiation.

The use of physiological measures in conjunction with subjective evaluation of the environmental and task-enduced stresses may have greater relevance in operation situations: a conclusion supported by the report of a significant correlation between finger tremor and the complexity of approach and landing.

Despite the considerable research effort which has been expended on the recording of physiological variables in real and simulated flight, the interpretation of such data in relation to pilot workload still awaits clarification.

THE COMPONENTS OF WORKLOAD

1. Physical Stresses

These were not discussed comprehensively, though the importance of thermal stress and its deleterious effect on pilot performance was underlined in two papers. Evidence was presented that pilot performance during helicopter flight was degraded and performance variability increased above a WBGT index of 85°F. There is a need for agreement on a measurement index which would maintain its validity in different environmental situations and allow "thermal stress" to be

operationally defined.

The contribution of abnormal force environments (e.g. vibration) to workload and the interaction of physical stresses were topics which unfortunately were not raised in formal communications or discussions.

2. Sleep Loss

The results of anamnestic studies indicated that accumulated sleep loss, often arising from the disruption of normal day-night duty cycles, was a major factor in the determination of long-term workload. Due attention to the organisation of duty sequences in relation to established diurnal patterns can do much to minimise sleep loss and maintain the operational efficiency of flying personnel. Experimental studies have shown that effective performance is more dependent upon the total amount of sleep obtained in the previous twenty-four hours than on the type of sleep. The use of drugs to obtain adequate sleep when working disruptive duty schedules was raised in discussion. It was apparent that more information was requested on the advantages and disadvantages of the pharmacological regulation of the sleep of aircrew.

3. The Flying Task

The importance of the approach and landing phase of flights as a period of high workload was emphasised by the fact that at least one third of the papers presented were concerned with some facet of this topic.

A study of the accuracy of approach and the success of landing on aircraft carriers analysed the factors which contribute to the degraded precision of approach and the higher accident rate during night operations. The need for better visual landing aids was adduced.

The errors associated with landing at night on conventional airfields is being studied with the aid of a special purpose simulator. It has been shown that pilots using visual cues alone are generally unable to judge a safe approach altitude when the terrain has an upwards slope: they fly too high when only the airfield lights are visible and they tend to use the pattern of city lights as a horizontal reference, even when this is in error. An increase in workload during a simulated night visual landing did not of itself cause a significant decrement in performance, although it interacted with terrain slope and pilot differences. The broad conclusions of this study, that night visual approach accidents would probably be less if instruments and other aids were employed during this critical phase of flight, is worthy of note.

Dr. A.J. Benson
Chairman, Behavioral Sciences Committee
AGARD

ATTENDANCE

R.A. ALKOV PhD
Head, Behavioral Sciences
Naval Safety Center
Norfolk, Va 23511, USA

T.H. ALLEN PhD
USAFSAM, Box 4228
Brooks AFB
Texas 78235, USA

H. ARNOFF
AIR 5313A2
Washington DC, USA

Dr. G. BENNETT
Civil Aviation Authority
Shell Mex House
Strand, London WC2, England

Dr. A.J. BENSON
RAF Institute of Aviation Medicine
Farnborough, Hants, England

Major J.A. BIRT, USAF
Hqs AMD (AMRH)
Brooks AFB
Texas 78235, USA

Major J.D. BOREN, USAF
USAFSAM (SMET)
Brooks AFB
Texas 78235, USA

W.R. BOYLES
HumRRO Division 6 (Avn)
P.O. Box 428
Fort Rucker, Ala 36360, USA

V.C. BRAGG PhD
USAFSAM
Audiology Function
Brooks AFB
Texas 78235, USA

Captain F.C. BREWER
Canadian Forces Hqs
Directorate of Aeronaut cal Engineering
200 Elgin Street, Room 1021
Ottawa, Ontario, Canada

C.A. BRICTSON PhD
Dunlap & Associates Inc
1454 Cloverfield Boulevard
Santa Monica, California 90404, USA

Captain J.H. BRITTON, MC, USN
Bureau of Medicine & Surgery (511)
Department of the Navy
Washington DC 20390, USA

A.A. BURROWS PhD
Director of Research (Sciences)
Douglas Aircraft Company
McDonnell Douglas Corporation
Long Beach, California, USA

R.T. CAMP Jr
Director, Basic Sciences Division
Aeromedical Research Unit
Box 577
Fort Rucker, Ala 36360, USA

P.W. CARO
HumRRO Aviation Division
P.O. Box 428
Fort Rucker, Ala 36360, USA

H.C. CLAMANN
USAF AMD
Brooks AFB
Texas 78235, USA

M.M. COHEN PhD
Leader, Psychology Research Team
Aerospace Crew Equipment Department
NADC Johnsville
Warminster, Pa 18974, USA

R.L. CRAMER
USAFSAM, Box 4248
Brooks AFB
Texas 78235, USA

Dr. F.G. CUMMING
Royal Aircraft Establishment
Farnborough, Hants, England

Lieutenant P.M. CURRAN
Naval Missile Center
Code 5342
Pt Mugu, California 93041, USA

Major D.B. DAWSON
Hqs AMD (AMRO)
Brooks AFB
Texas 78235, USA

Group Captain T.G. DOBIE, OBE, RAF
Deputy Director of Aviation Medicine
Ministry of Defence
1-6 Tavistock Square
London WC1, England

P.J. DOWD
USAFSAM
Brooks AFB
Texas 78235, USA

Dr. E.R. DUSEK
Director, Behavioral Sciences Laboratory
US Army Research Institute of Environmental Medicine
Natick, Mass 01760, USA

Colonel W.B. FAVORITE, USAF
AGARD/NATO
7 rue Ancelle
92 Neuilly sur Seine, France

Lt.Colonel G. FROEHLICH, GAF, MC
Flugmedizinisches Institut der Luftwaffe
808 Fürstenfeldbruck, Germany

Brigadier General H. FUCHS, GAF, MC
Surgeon General, GAF
505 Porz-Wahn 2
Postfach 5000/501/16
Germany

Lieutenant P.A. FURR, USN
BuMed, Navy Department
Washington DC, USA

Lt.Colonel K. GERBERT, GAF, MC
Flugmedizinisches Institut der Luftwaffe
808 Fürstenfeldbruck, Germany

Lt.Colonel R.V. GONZALES, USA
US Army Human Research Unit
Fort Rucker, Ala 36360, USA

J.W. GREENE
Acoustics Laboratory, NAMI
Naval Aerospace Medical Center
Pensacola, Fla 32512, USA

Lt.Colonel K. GREGORY
USABAAR
Fort Rucker, Ala 36360, USA

Lt.Colonel H. GRUNHOFER, GAF, MC
Head, Division I
Flugmedizinisches Institut der Luftwaffe
808 Fürstenfeldbruck, Germany

R. HALVERSON
Head, Biomedical Sciences
Naval Safety Center
Norfolk, Va 23511, USA

C.S. HARRIS
Aerospace Medical Research Laboratory
Wright-Patterson AFB
Ohio 45433, USA

B.O. HARTMAN
Chief, Psychobiology Section (SMKN)
USAFSAM, Box 4275
Brooks AFB
Texas 78235, USA

Captain F.H. HAWKINS
KLM Royal Dutch Airlines
Schipol Airport, Amsterdam, Netherlands

Captain R.Y. HICKS
USARIEM
Natick, Mass 01760, USA

Captain L.E. HILL
c/o BOAC 707 Flight
London Heathrow Airport, England

Captain M.A. HOFMANN
USAARL
Box 577
Fort Rucker, Ala 36360, USA

Dr. J.S. HOWITT
Board of Trade (Aviation Department)
Shell Mex House
Strand, London WC2, England

Captain A.L. HUGHES
USARIEM
Natick, Mass 01760, USA

Captain L.G. INNES
Canadian Armed Forces (Air)
1107 Avenue Road
Toronto 305, Ontario, Canada

L.C. JOHNSON
Head, Psychology Division
Navy Medical Neuropsychiatric Research
San Diego, California 92152, USA

Lt.Commander J.H. JOHNSON
Commander
Fleet Air Wings Atlantic, NAS
Norfolk, Va 23511, USA

Colonel L.F. JOHNSON, USAF, MC
AMD (AMF)
Brooks AFB
Texas 78235, USA

R.D. JONES
Commanding Officer, USAHEL (AMXHE-SYS)
Aberdeen Proving Ground
Maryland 21005, USA

J.W.H. KALSBEEK PhD
TNO Health Organisation
20 1st Const. Huygensstraat
Amsterdam, Netherlands

Commander T.E.M. KIRBY, RN
Officer Commanding, Flying Wing
Royal Aircraft Establishment
Bedford, England

Dr. K.E. KLEIN
532 Bad Godesberg
DVLR
Kölnerstrasse 70
Germany

Major S. KNAPF
USAARL, Box 577
Fort Rucker, Ala 36360, USA

C.L. KRAFT
The Boeing Company
Military Aircraft Systems
Division 23-28
Seattle, Washington, USA

Professor Dr. E.A. LAUSCHNER
Brigadier General, GAF, MC
Flugmedizinisches Institut der Luftwaffe
808 Fürstenfeldbruck, Germany

Lt.Colonel D.E. LITTELL
USAARL, Box 577
Fort Rucker, Ala 36360, USA

Colonel R.S. MALONE, USAF, MC
Chief, Medical Research Group
Hqs USAF (AFMSIG)
Washington DC 20333, USA

Dr. D.E. MEYER
AFHRL
HRC, Human Resources Laboratory
Brooks AFB
Texas 78235, USA

S. MORELAND
C.O. USAHEL (AMXHE-SYS)
Aberdeen Proving Ground
Maryland 21005, USA

J.G. NELSON
LSEHA-2
Naval Air Development Center Johnsville
Warminster, Pa 18974, USA

Lt.Commander P.D. NELSON
Bureau of Medicine & Surgery (713)
Department of the Navy
Washington DC, USA

Squadron Leader A.N. NICHOLSON, RAF
RAF Institute of Aviation Medicine
Farnborough, Hants, England

C.W. NIXON
AMRL (MRBA)
Wright-Patterson AFB
Ohio 45433, USA

W.P. ORRICK Jr
NADC
Warminster, Pa 18974, USA

Lt.Colonel C.D. OVERFELT, USAF, MC
USAFSAM (SMT)
Brooks AFB
Texas 78235, USA

B.D. PARKER
Decca Navigator Company Limited
247 Burlington Road
New Malden, Surrey, England

Lt.Colonel D.P. PARKS, USAF
Office of the Surgeon General
Hqs USAF (AFMSPG)
Washington DC 20333, USA

Captain I.C. PERRY, RAMC
Hqs Army Aviation
Middle Wallop, Hants, England

D.M. PETRIE
The Boeing Company
Box 3707
Seattle, Washington, USA

Professor S. QUIST-HANSSEN
Institute of Audiology
University Hospital Rikshospitalet
Dept of Oto-Laryngology
Oslo, Norway

J.M. RING
AMRL
Wright-Patterson AFB
Ohio 45433, USA

Colonel N. RHEMREN, RNethAF
le van den Boschstraat 8
The Hague, Netherlands

Dr H.P. RUFFELL-SMITH
55 Hallam Court
London W.1, England

Major D.T. SANDERS, MC, USA
Chief, Aviation Medicine Research Branch
US Army Med R&D Command (MEDDH-RPA)
Washington DC 20315, USA

A.S. SANTANELLI
ECOM, Avionics Laboratory
AMSEL-VL-I
Fort Monmouth, New Jersey, USA

Lt.Colonel G.A. SCHIRRMANN, GAF
8 Munich 90
Agilolfingerstrasse 24
Germany

Lt.Colonel C.G. SEVESTRE, FAF
AGARD/NAT
7 rue Anc[illegible]e
92 Neuilly sur Seine, France

Colonel R.H. SHAMBUREK, MC, USA
AvnBr, D/P S&O
Office of the Surgeon General
Department of the Army
Main Navy Building
Washington DC 20315, USA

J.M. SHAW
Engineering Physics Department
Royal Aircraft Establishment
Farnborough, Hants, England

Major J. SOUTENDAM
Canadian Forces Institute of Environmental
Medicine (Air)
1107 Avenue Road
Toronto 305, Ontario, Canada

S.E. STUNTZ
Stanford Research Institute
Menlo Park, Calif 94025, USA

H.C. SUTHERLAND Jr
USAFSAM
Brooks AFB
Texas 78235, USA

R.P. TEGT
Naval Missile Center (Code 5336)
Pt Mugu, Calif 93041, USA

Lt.Colonel V.H. THALER, USAF
AMRL
Wright-Patterson AFB
Ohio 45433, USA

Dr. [illegible] THOMSON
Naval Air Test Center
Code 35A, Aeromedical Branch, ST
NATC
Patuxent River, Md 20670, USA

Dr G.C. TOLHURST
Director, Physiological Psychology Branch
Office of Naval Research
Dept of the Navy
Washington DC 20360, USA

Captain R.W. TRIMBLE, USAF
USAFSAM (SMENH)
Brooks AFB
Texas 78235, USA

Dr M.J. WARRICK
AMRL (MRH)
Wright- Patterson AFB
Ohio 45433, USA

J.C. WEBSTER
US Navy Electronics Lab Center
San Diego, Calif 92152, USA

Dr H.M. WEGMANN
DVLR
Kölnerstrasse 70
532 Bad Godesberg, Germany

Dr M.A. WHITCOMB
National Academy of Sciences
2101 Constitution Avenue, NW
Washington DC 20418, USA

Group Captain [illegible] WHITESIDE, MBE, RAF
RAF Institute of Aviation Medicine
Farnborough, Hants, England

R.P. WHITTEN
4715 Glasgow Drive
Rockville, Maryland, USA

Dr C.E. WILLIAMS
NAMI
Pensacola, Fla 32512, USA

J.W. WOLFE
Director of Research, SMKE-V
USAFSAM, Box 4009
Brooks AFB
Texas 78235, USA

Dr J.W. WULFECK
Dunlap & Associates Inc
1454 Cloverfield Boulevard
Santa Monica, Calif 90404, USA

L.P. ZAITZEFF
MASD M.S. 23-28
The Boeing Company
P.O. Box 3707
Seattle, Washington, USA

Dr H.F. ZETZMANN
DVLR
8031 Oberpfaffenhofen
Post Wessling, Germany